

# The MEG experiment at PSI

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for the MEG collaboration



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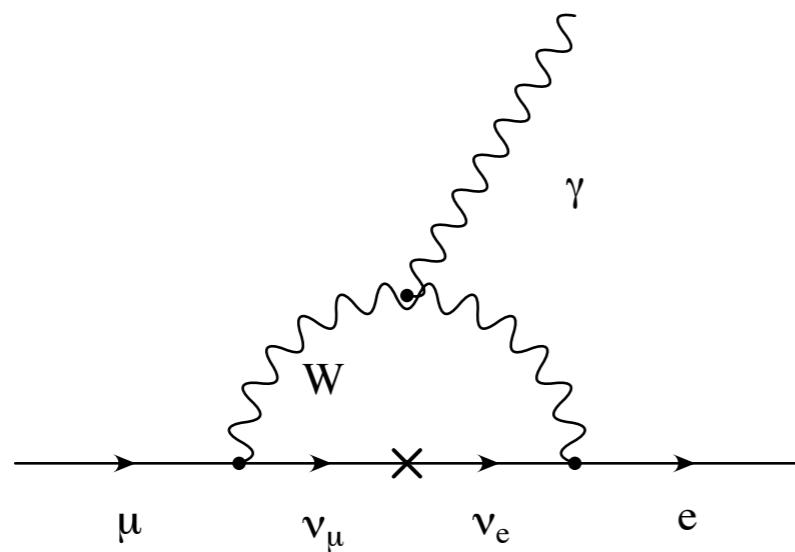


# Outline

- Physics **motivation** for a  $\mu \rightarrow e\gamma$  experiment
- The  $\mu \rightarrow e\gamma$  decay
- The **detector**
  - Beam line & target
  - Spectrometer
  - Timing Counter
  - LXe calorimeter
  - Calibrations
  - Electronics
- **Status**
- Future

# The $\mu \rightarrow e\gamma$ decay

- The  $\mu \rightarrow e\gamma$  decay is **forbidden** in the **SM** because of the (accidental) conservation of lepton family numbers
- The introduction of **neutrino masses and mixings** induces  $\mu \rightarrow e\gamma$  radiatively, but at a negligible level

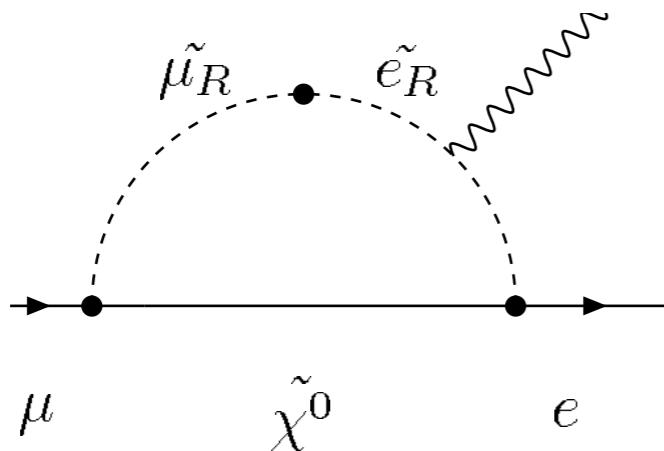


$$\Gamma(\mu \rightarrow e\gamma) \approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left( \frac{\alpha}{2\pi} \right) \sin^2 2\theta \sin^2 \left( \frac{1.27\Delta m^2}{M_W^2} \right)$$

BR  $\sim 10^{-55}$

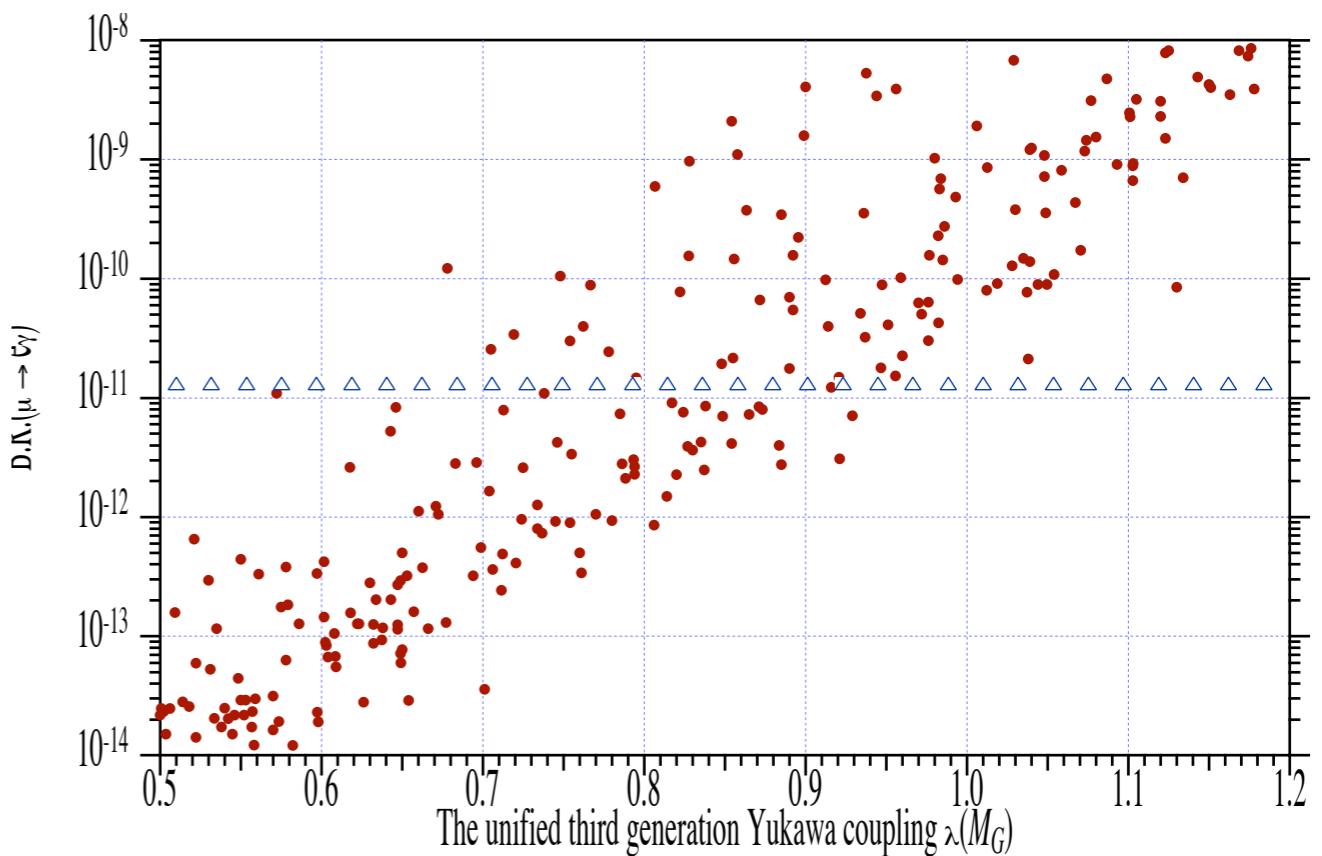
- All **SM extensions enhance the rate** through mixing in the high energy sector of the theory

# For instance... predictions

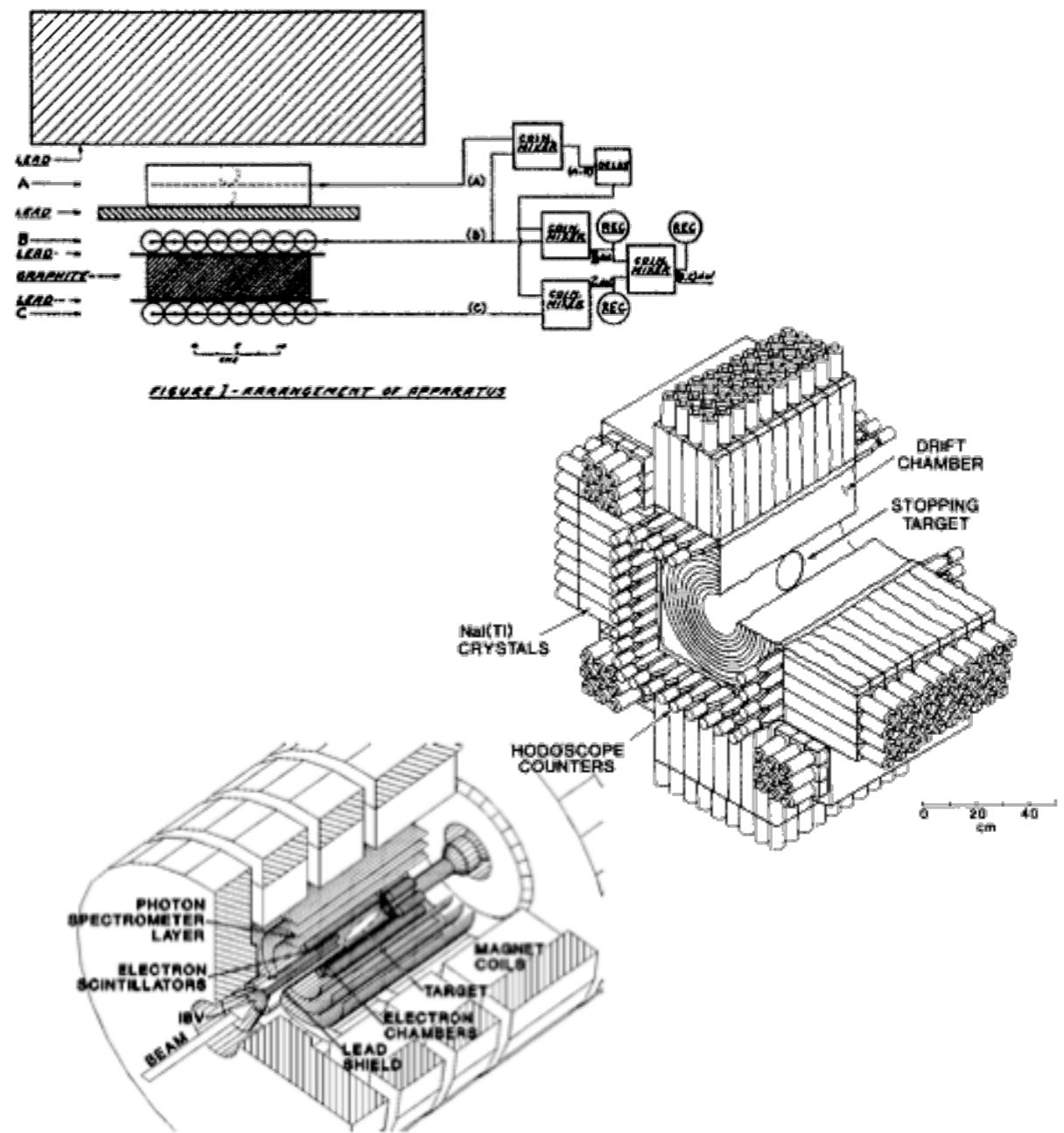
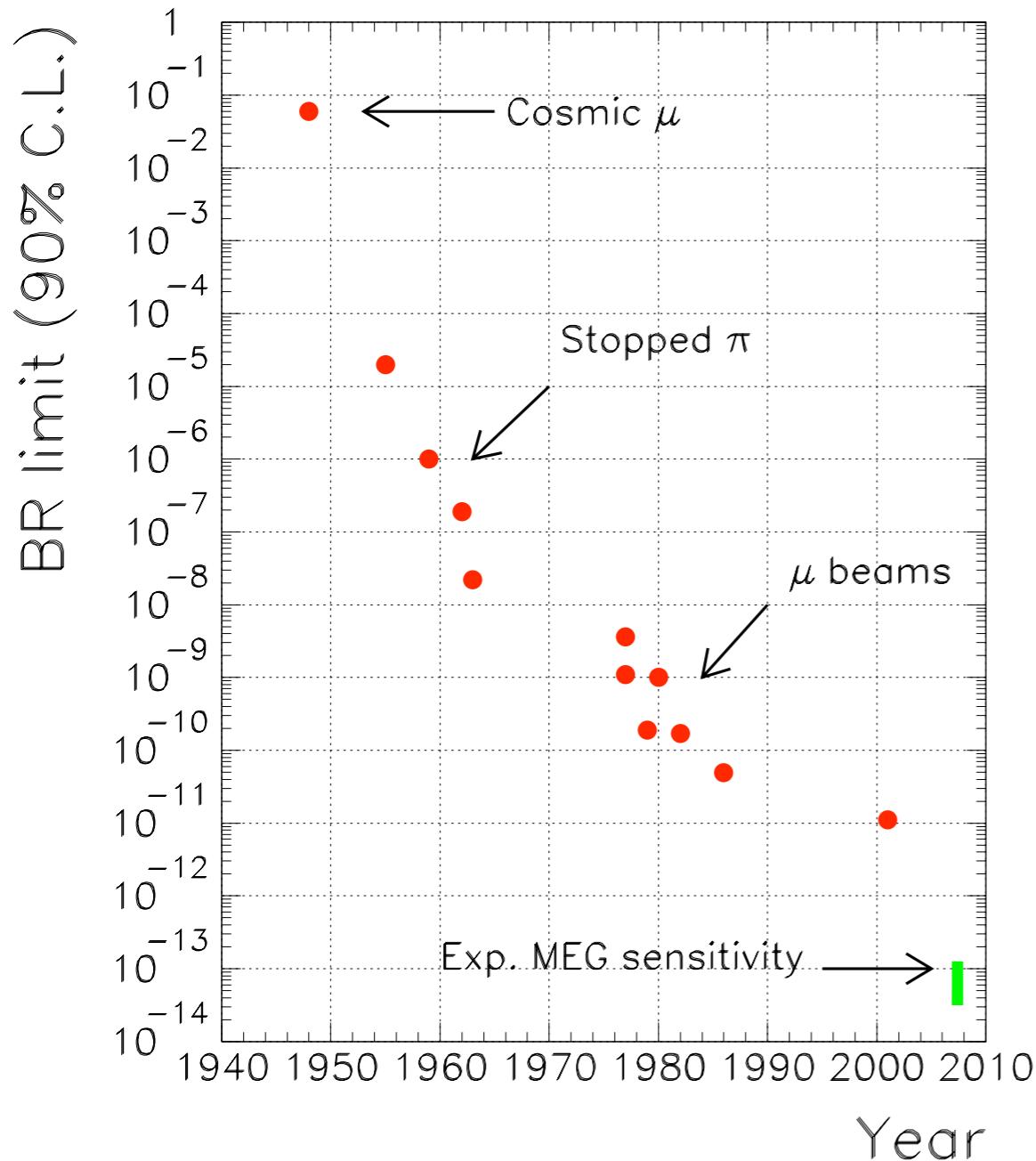


- **SUSY SU(5)** predictions: LFV induced by finite slepton mixing through radiative corrections. The mixing could be large due to the top-quark mass at a level of  $10^{-12}$   $10^{-15}$
- **SO(10)** predicts even larger BR:
  - $m(\tau)/m(\mu)$  enhancement
- Models with **right-handed neutrinos** also predict large BR
- $\Rightarrow$  clear evidence for physics beyond the SM.

R. Barbieri et al., Nucl. Phys. B445 (1995) 215  
 J. Hisano et al., Phys. Lett. B391 (1997) 341  
 R. Ciafaloni, A. Romanino, A. Strumia, Nucl. Phys. B458 (1996)  
 J. Hisano, N. Nomura, Phys. Rev. D59 (1999)



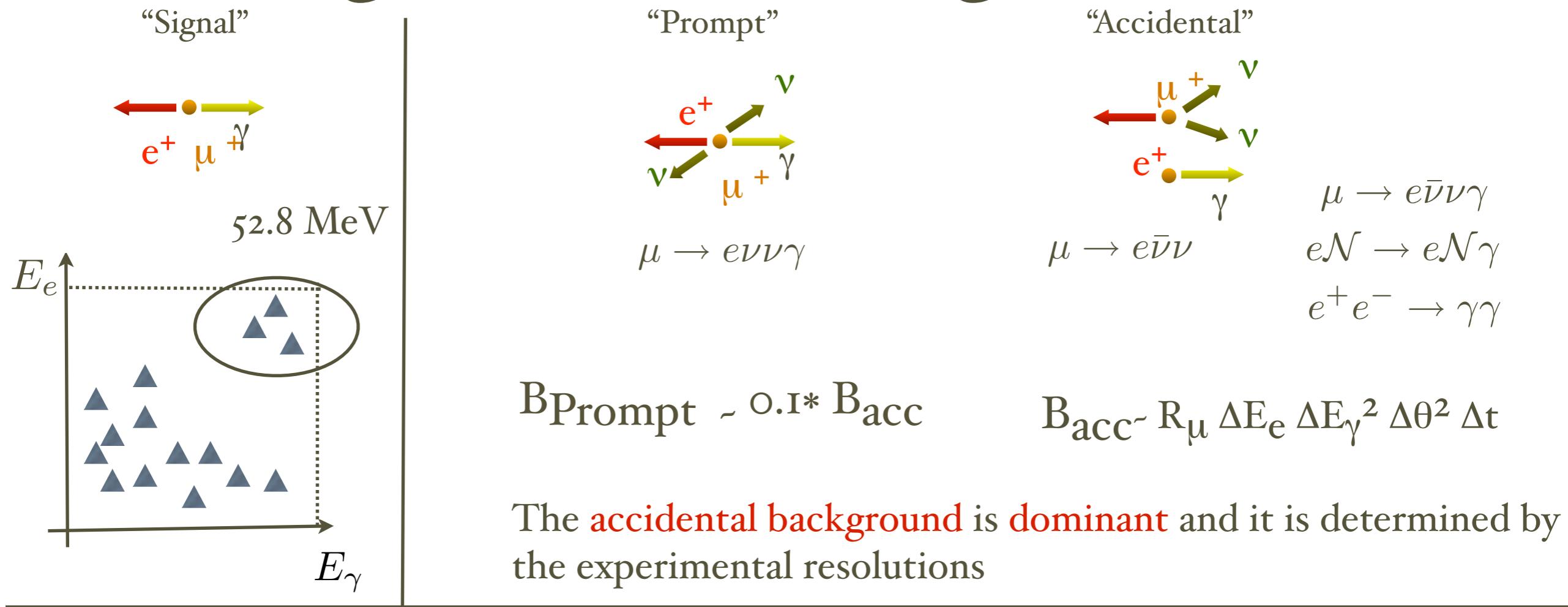
# Historical perspective



Each improvement linked to an  
**improvement in the technology**

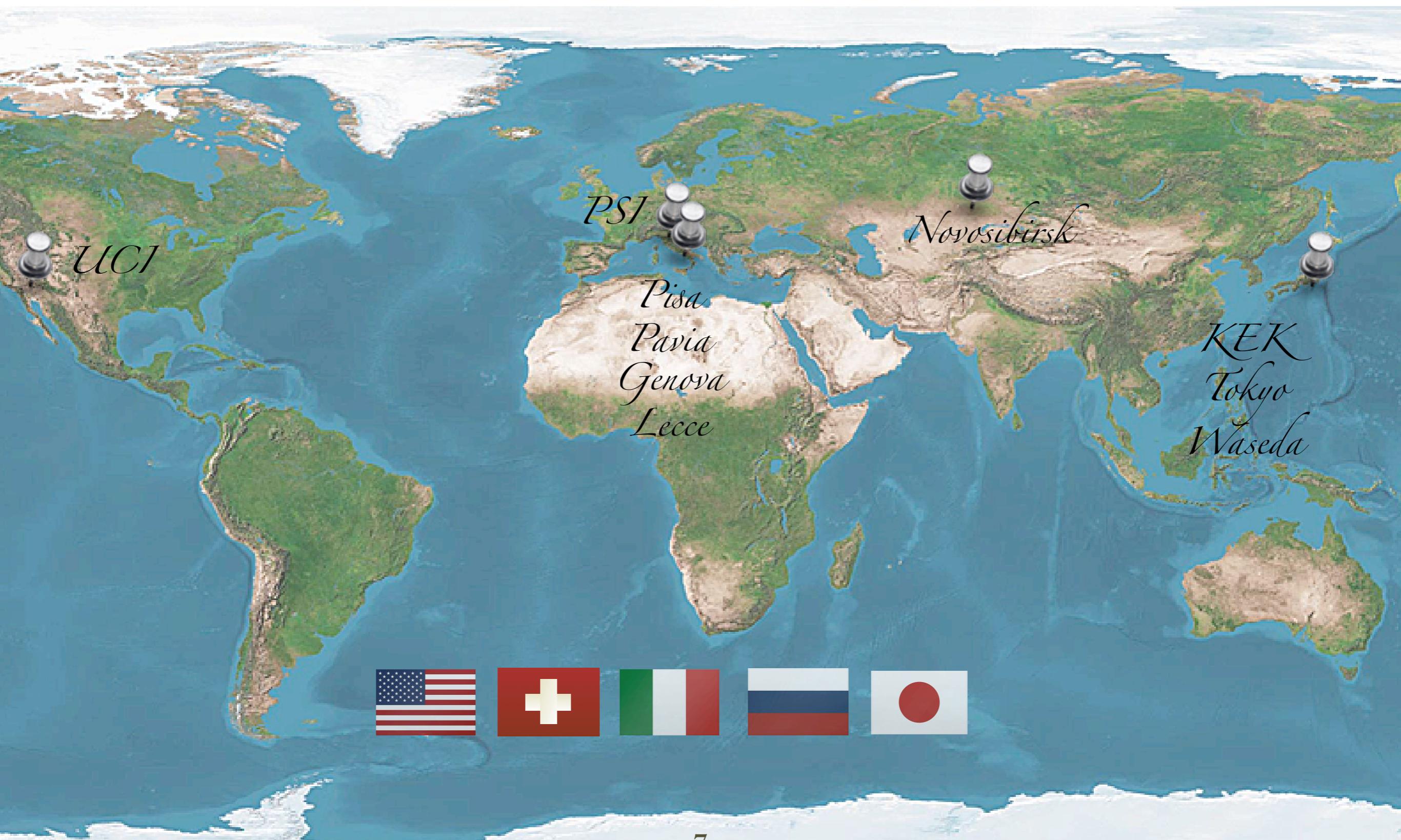
$$N_{\text{sig}} = R_\mu T \frac{\Delta\Omega}{4\pi} \epsilon_\gamma \epsilon_e \epsilon_{\text{cut}} B_{\mu \rightarrow e\gamma}$$

# Signal and Background



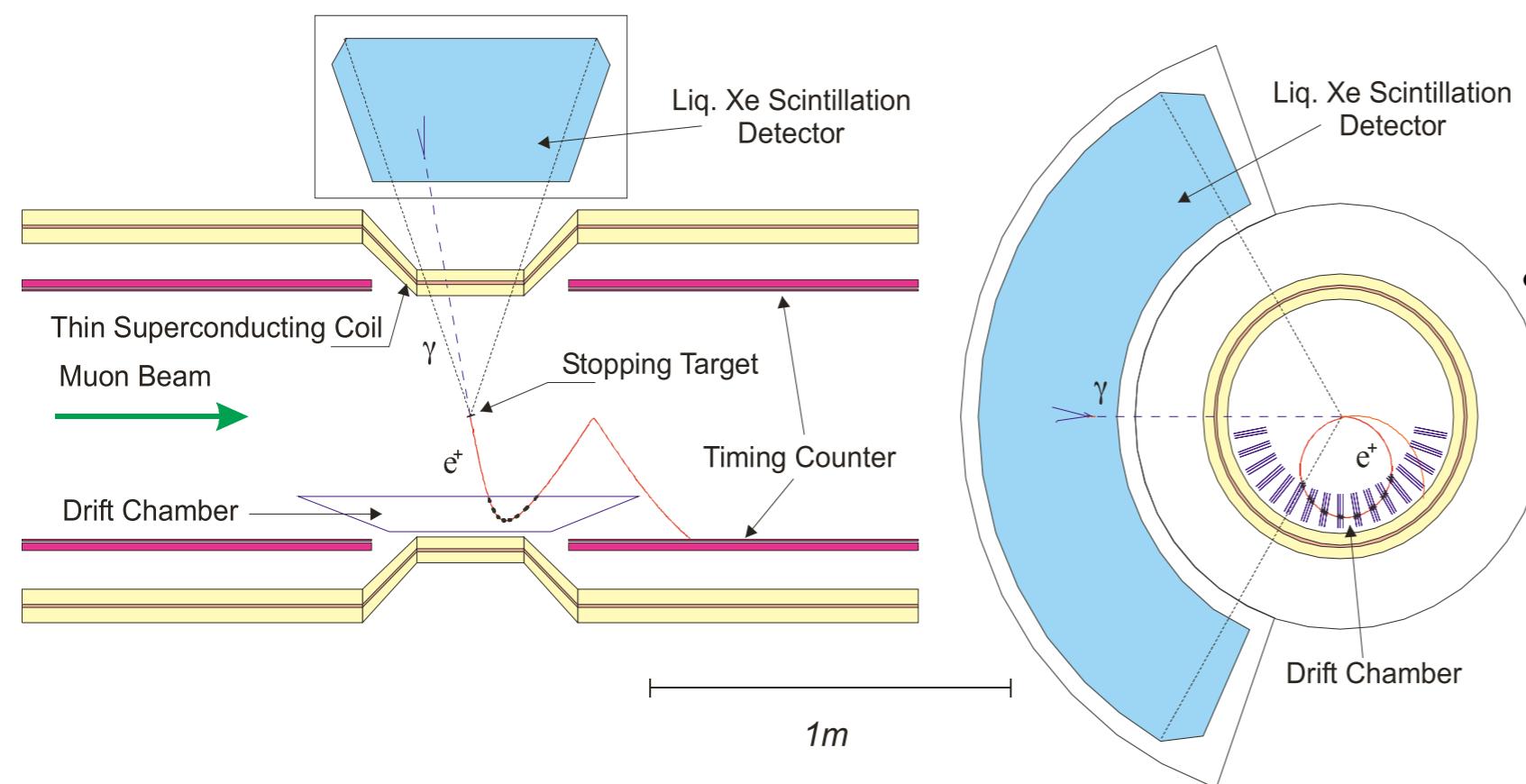
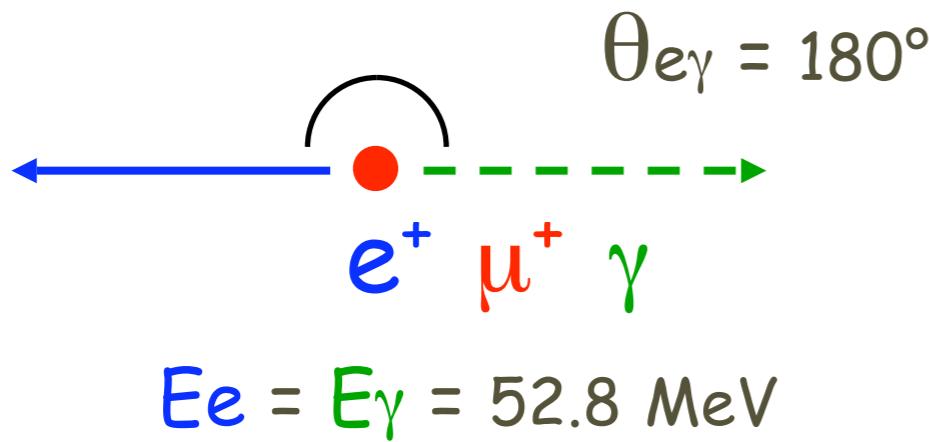
Exp./Lab	Year	$\Delta E_e/E_e$ (%)	$\Delta E_\gamma/E_\gamma$ (%)	$\Delta t e \gamma$ (ns)	$\Delta \theta e \gamma$ (mrad)	Stop rate ( $s^{-1}$ )	Duty cyc. (%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	$5 \times 10^5$	100	$3.6 \times 10^{-9}$
TRIUMF	1977	10	8.7	6.7	-	$2 \times 10^5$	100	$1 \times 10^{-9}$
LANL	1979	8.8	8	1.9	37	$2.4 \times 10^5$	6.4	$1.7 \times 10^{-10}$
Crystal Box	1986	8	8	1.3	87	$4 \times 10^5$	(6..9)	$4.9 \times 10^{-11}$
MEGA	1999	1.2	4.5	1.6	17	$2.5 \times 10^8$	(6..7)	$1.2 \times 10^{-11}$
MEG	2006	0.8	4	0.15	19	$2.5 \times 10^7$	100	$1 \times 10^{-13}$

# The MEG Collaboration



# MEG experimental method

Easy signal selection with  $\mu^+$  at rest



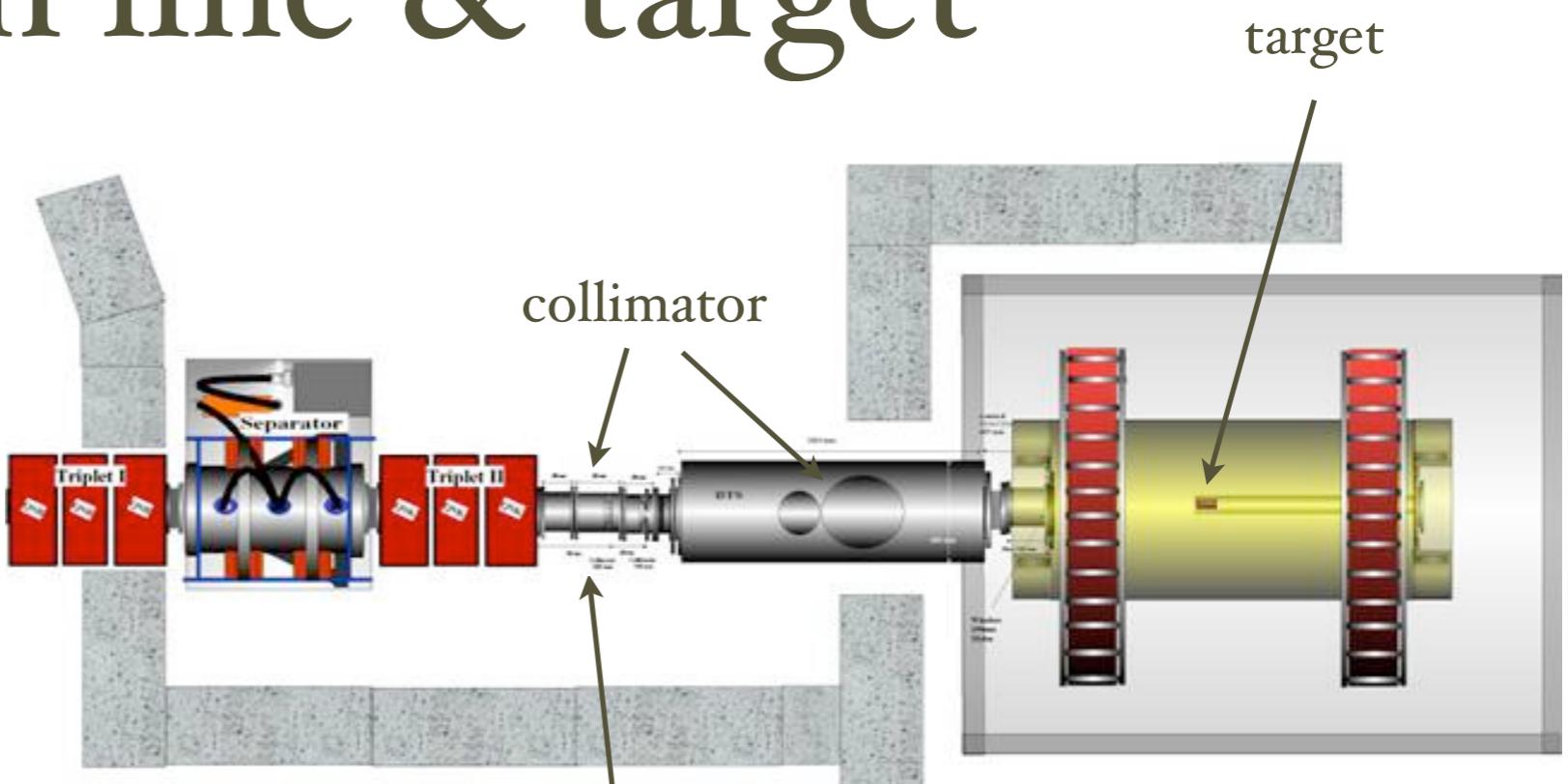
- Stopped beam of  $>10^7 \mu/\text{sec}$  in a  $150 \mu\text{m}$  target
- $\gamma$  detection  
Liquid Xenon calorimeter based on the scintillation light
  - fast: 4 / 22 / 45 ns
  - high LY:  $\sim 0.8 * \text{NaI}$
  - short  $X_o$ : 2.77 cm
- $e^+$  detection  
magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum  
scintillation counters for timing

# Beam line & target

$\pi E_5$  beam line at PSI

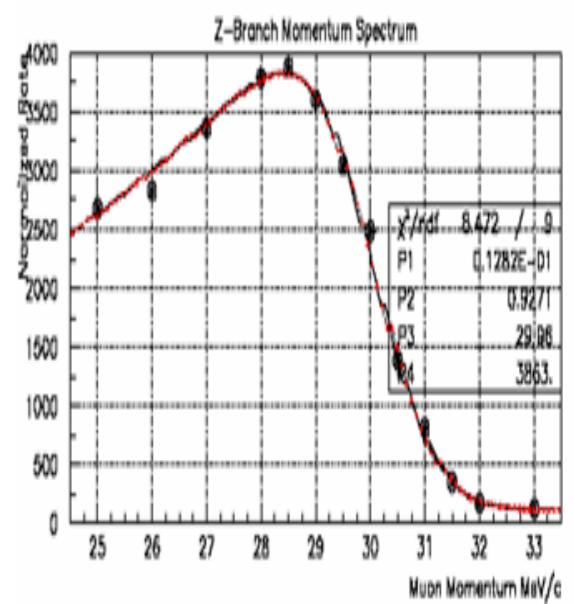
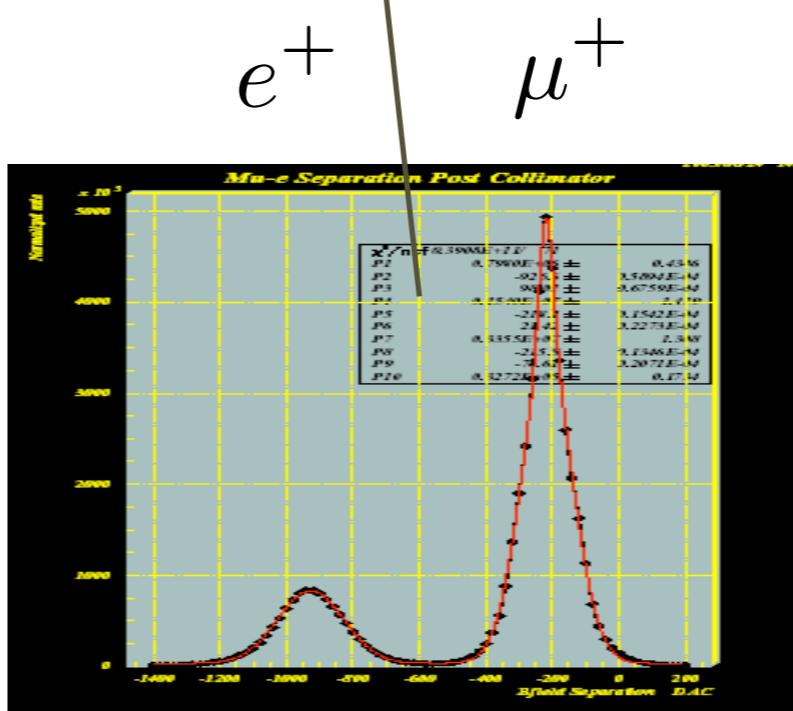
Optimization of the beam elements:

- Muon momentum  $\sim 29$  MeV/c
- Wien filter for  $\mu/e$  separation
- Solenoid to couple beam and spectrometer (BTS)
- Degrader to reduce the momentum for a 150  $\mu\text{m}$  target

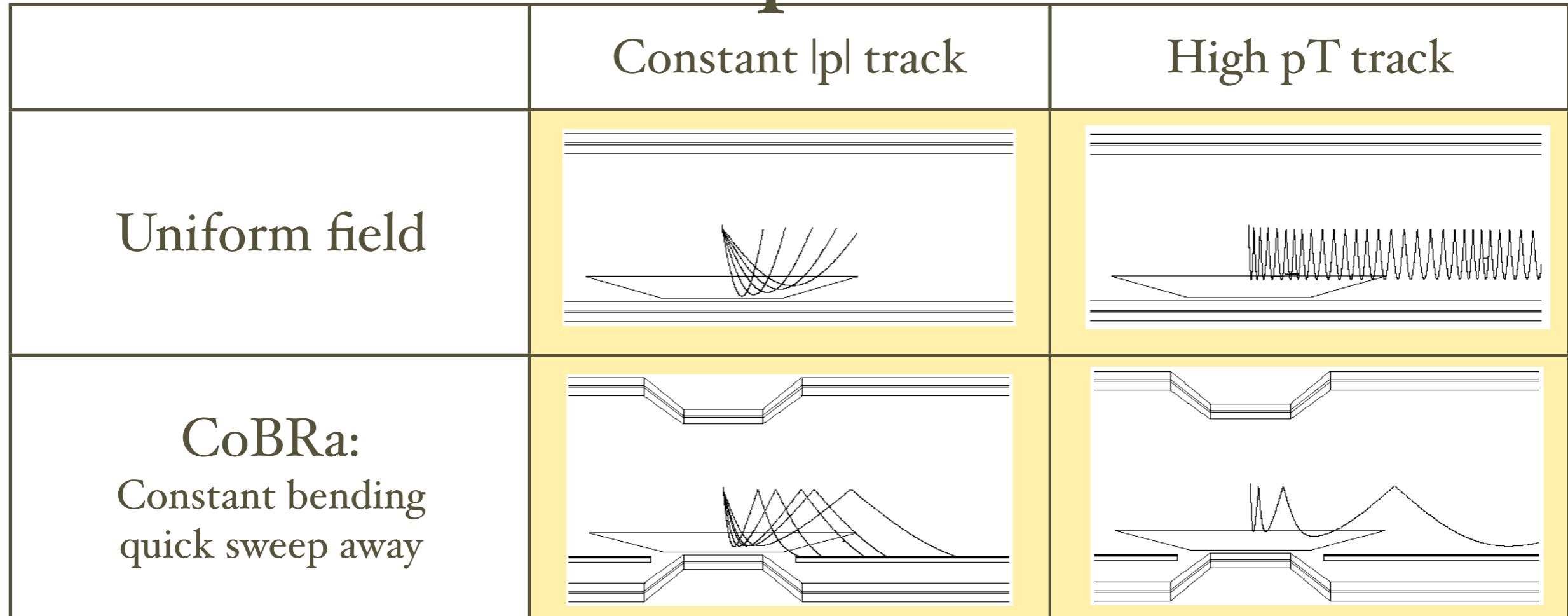


Present results (1.8 mA):

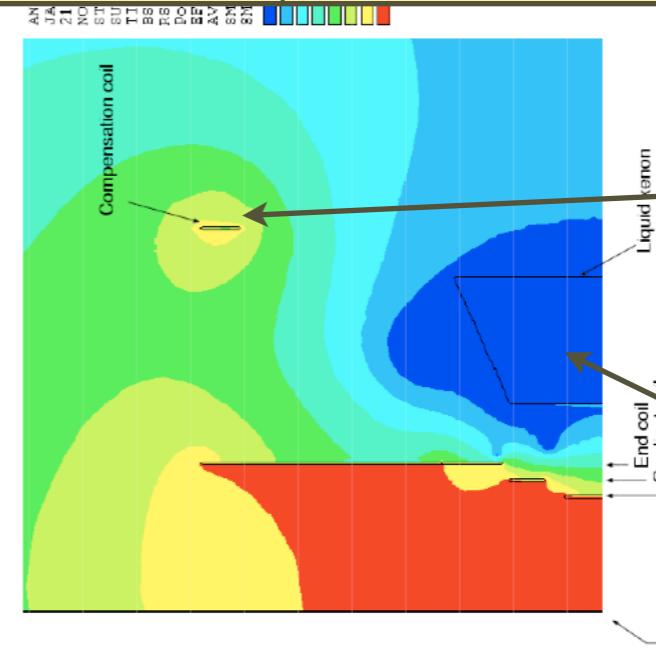
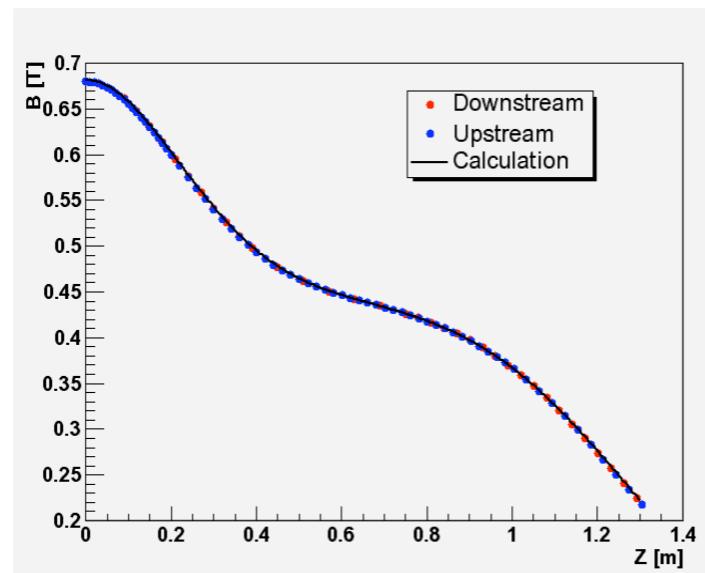
- $R_\mu$  (total)  $1.3 \times 10^8 \mu^+/\text{s}$
- $R_\mu$  (after Triplet 2)  $9.4 \times 10^7 \mu^+/\text{s}$
- $\mu/e$  separation  $11.8 \text{ cm} (7.2 \sigma)$
- $R_\mu$  (exp. on target)  $6.4 \times 10^7 \mu^+/\text{s}$
- $\mu$  spot (exp. on target)  $\sigma_V \approx \sigma_H \approx 10 \text{ mm}$



# COBRA spectrometer

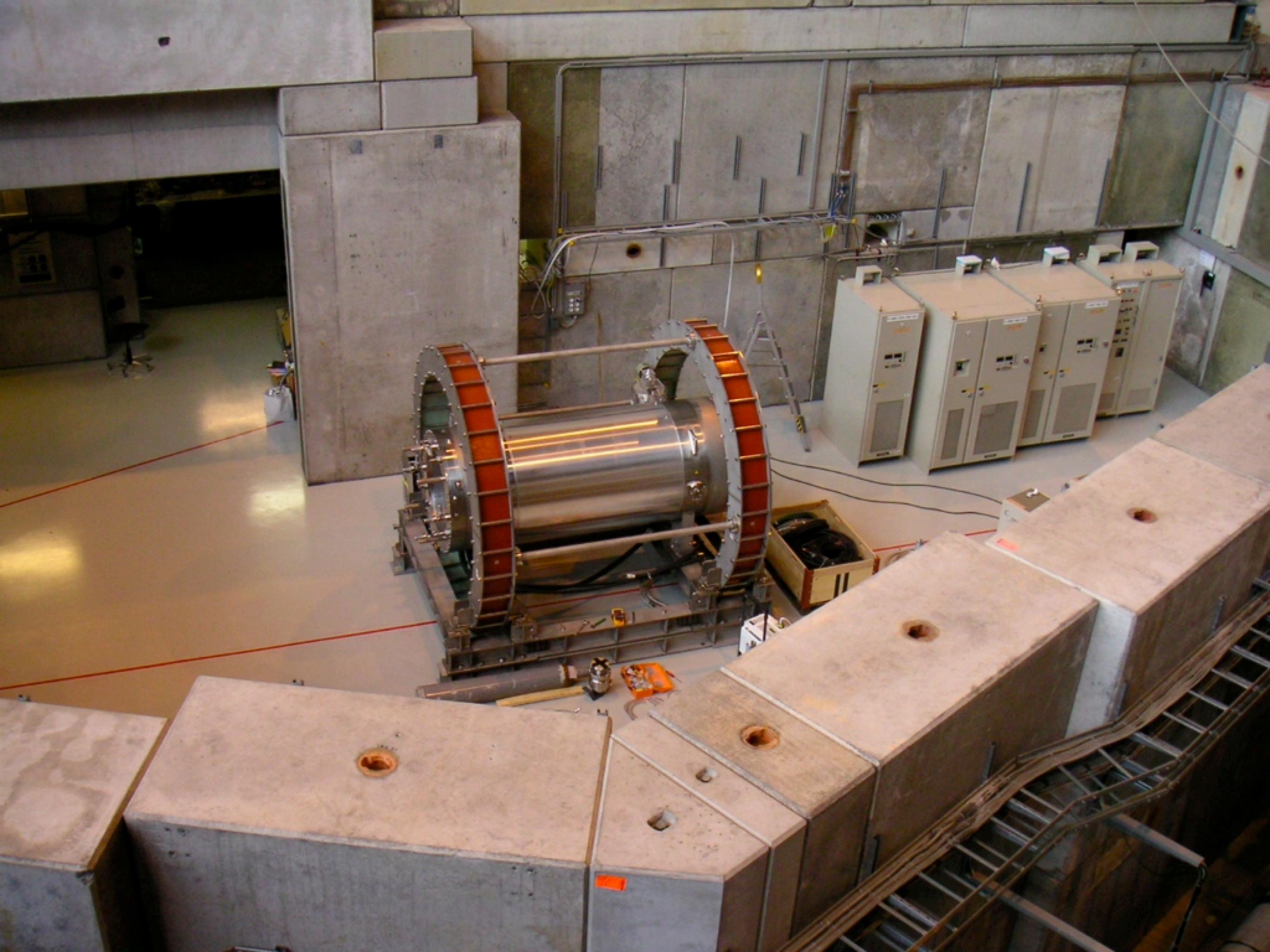


Non uniform magnetic field decreasing from the center to the periphery

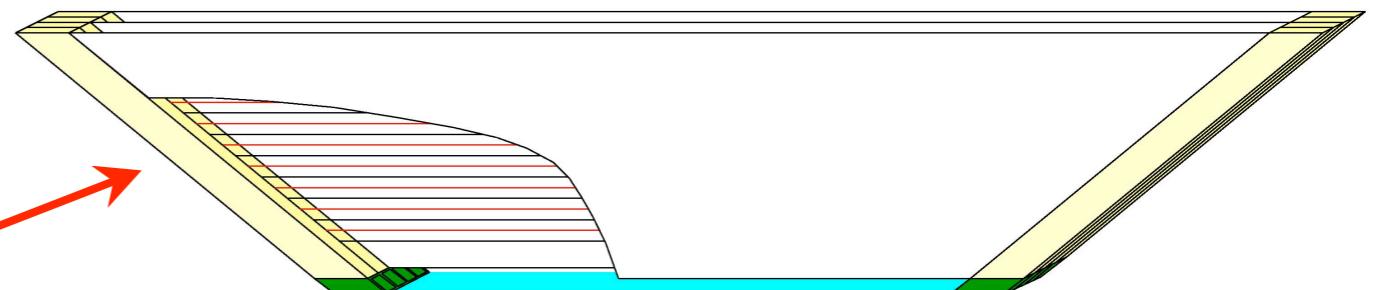
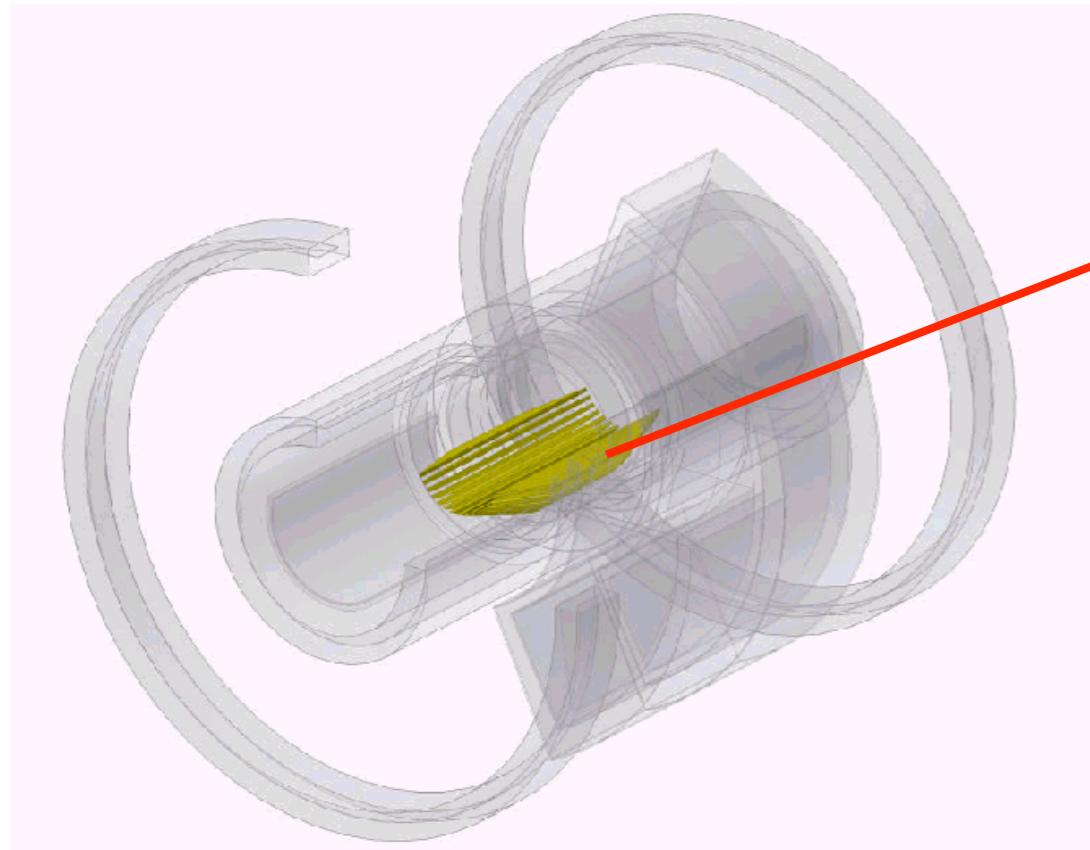


Compensation coil for LXe calorimeter

$$|\vec{B}| < 50 \text{ G}$$

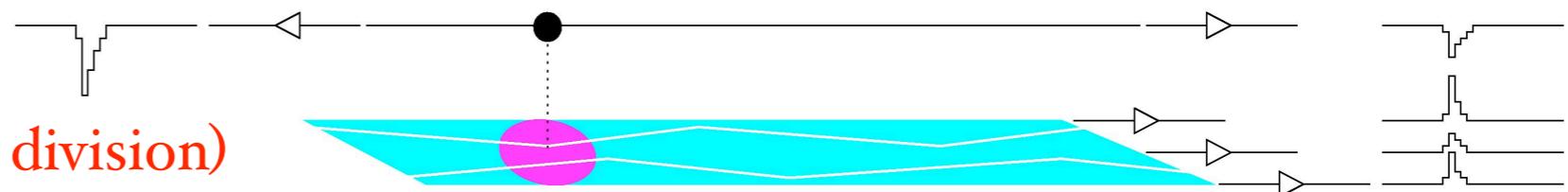


# Positron Tracker



- 16 chambers radially aligned with 10° intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 vernier cathode strips made of 15 µm kapton foils and 0.45 µm aluminum strips
- Chamber gas: He-C<sub>2</sub>H<sub>6</sub> mixture

transverse coordinate (t drift)

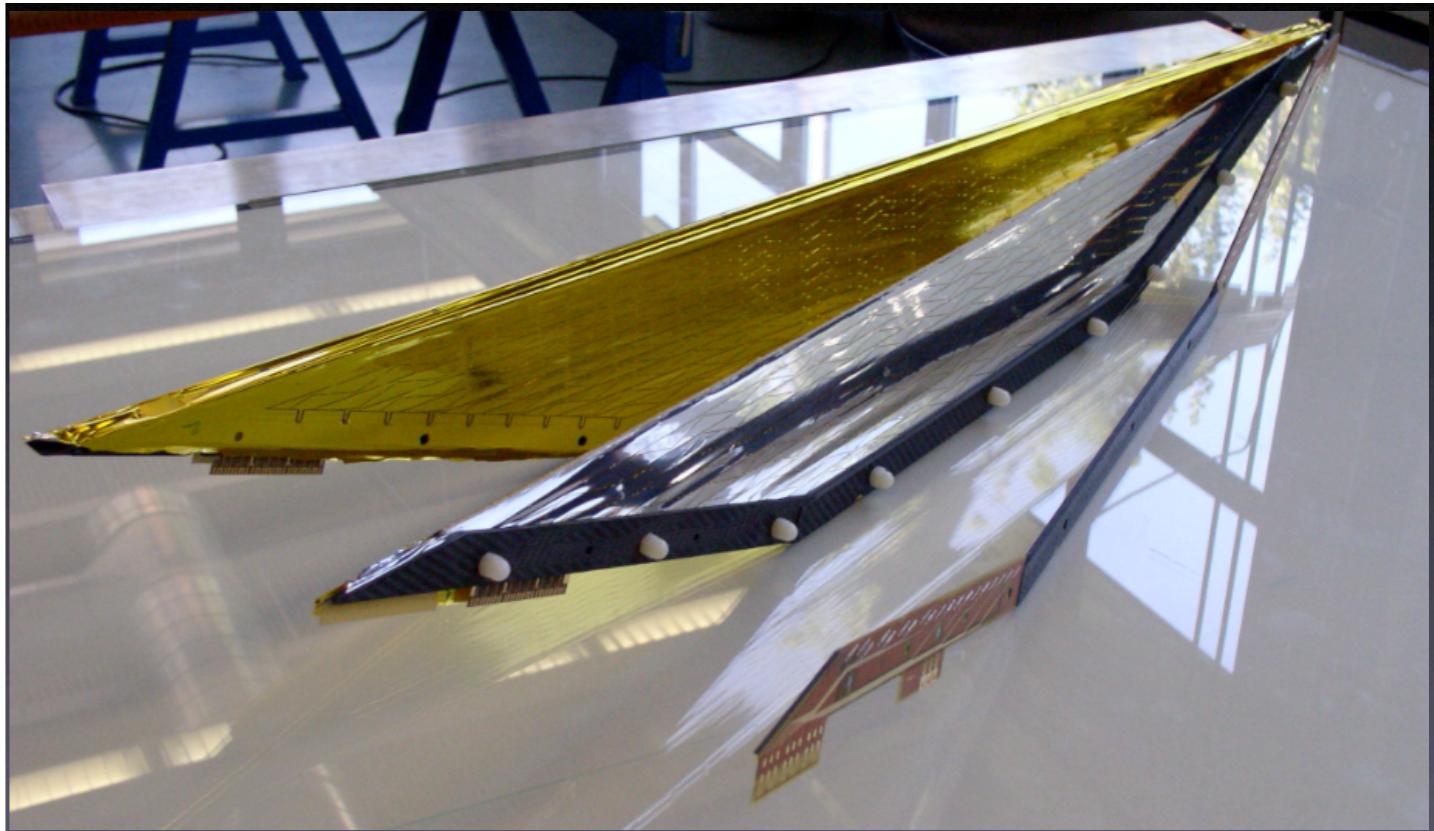
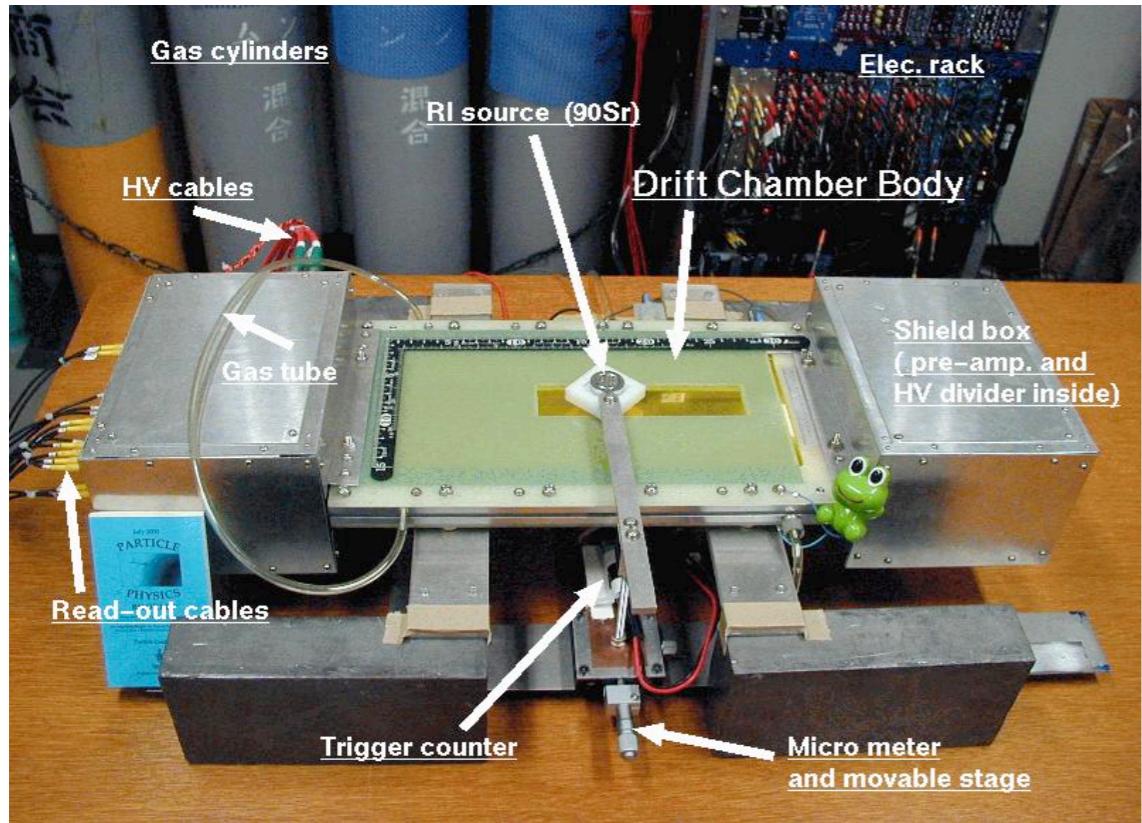


Measurements at Tokyo University:

$$\sigma_R = 93 \pm 10 \mu\text{m}$$

$$\sigma_Z = 425 \pm 7 \mu\text{m}$$

# Drift chambers



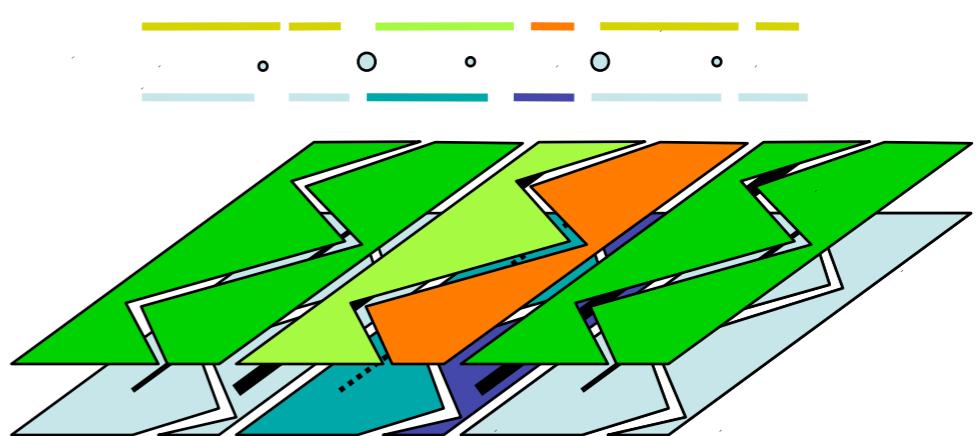
- Full scale test in November
- Summary of Drift Chamber simulation

$$\delta P_{e^+} / P_{e^+} = 0.7 \div 0.9\%$$

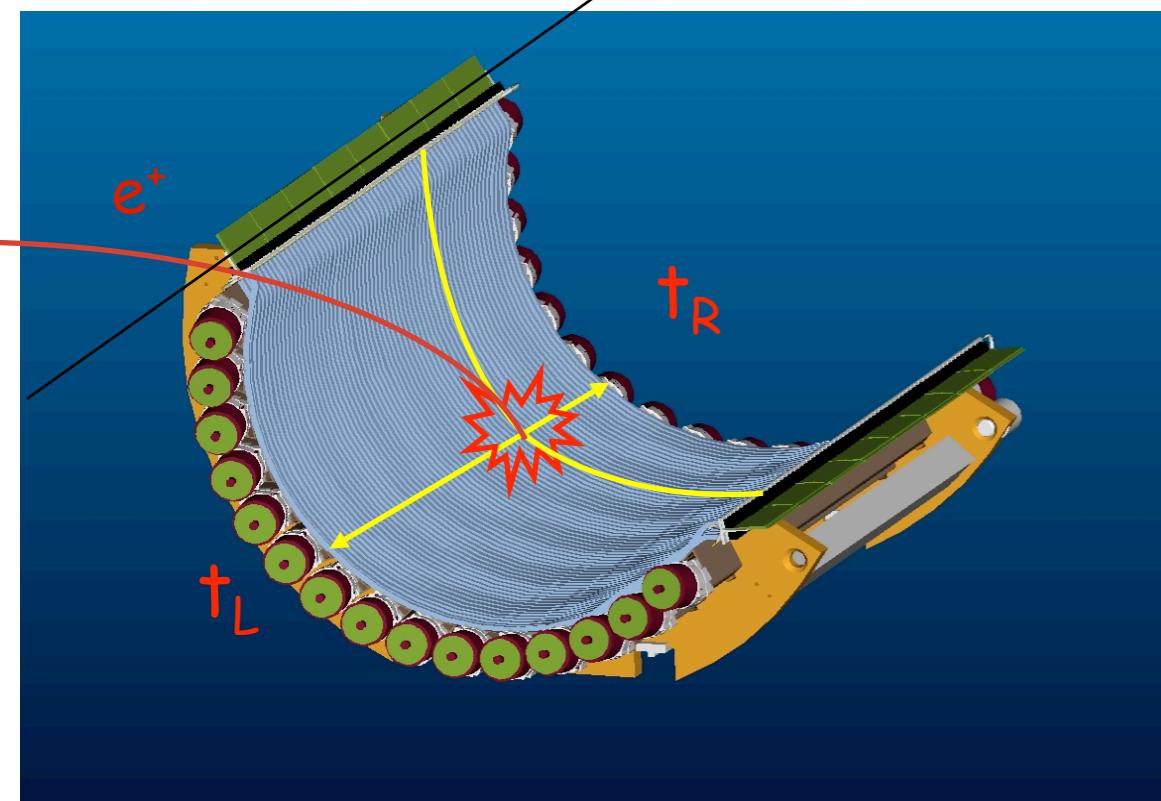
$$\delta\theta_{e^+} = 9 \div 12 \text{ mrad}$$

$$\delta x_{orig} = 2.1 \div 2.5 \text{ mm}$$

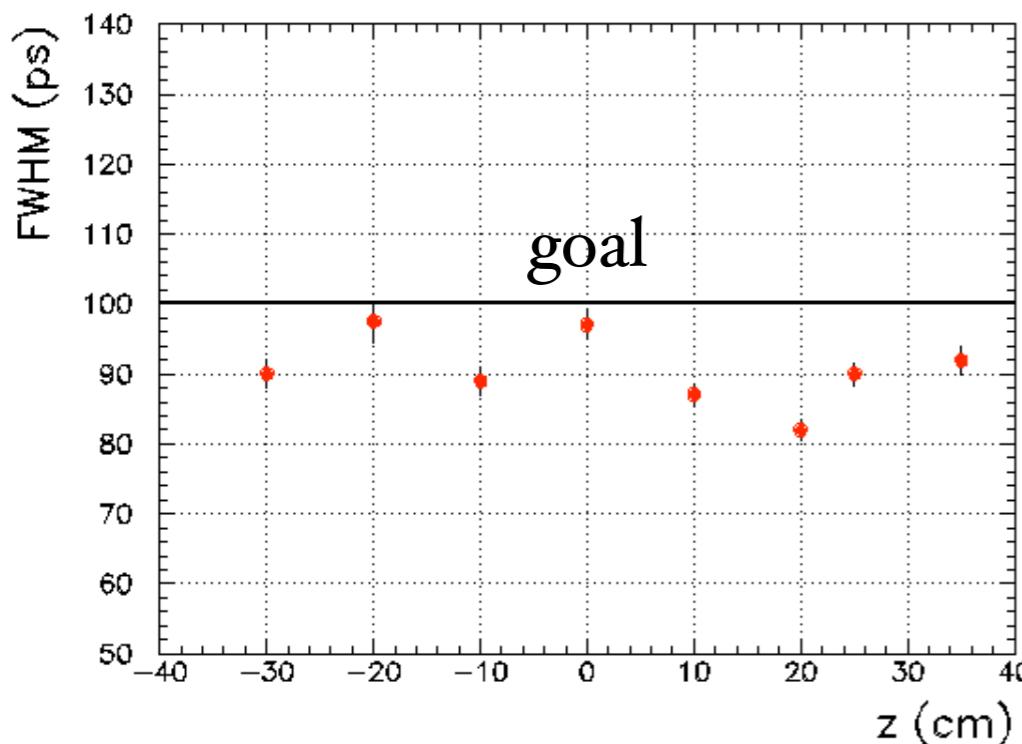
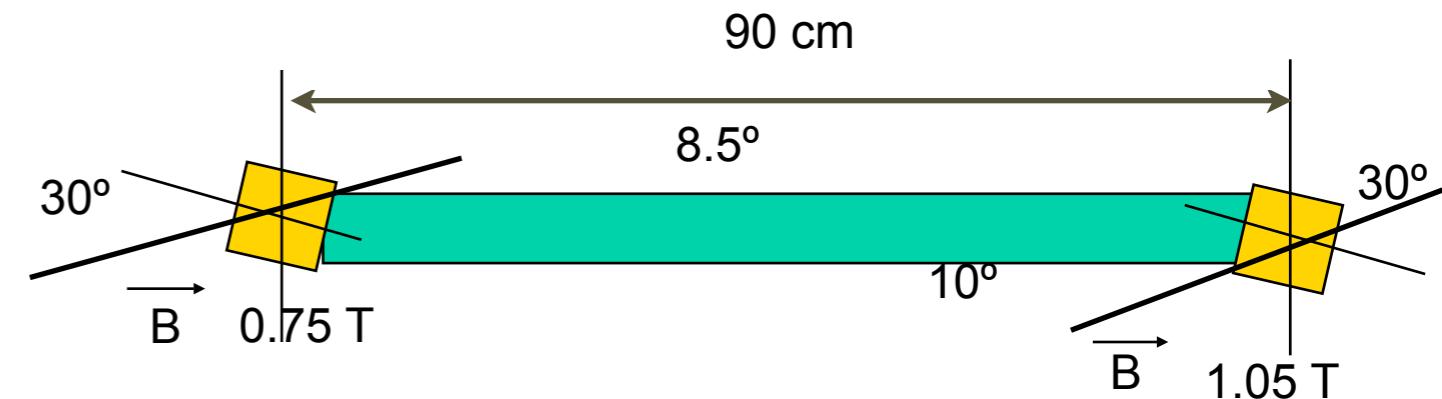
FWHM



# Timing Counter



- Two layers of scintillators:  
Outer layer, read out by PMTs: timing measurement  
Inner layer, read out with APDs at  $90^\circ$ : z-trigger
- Obtained goal  $\sigma_{\text{time}} \sim 40 \text{ psec}$  (100 ps FWHM)

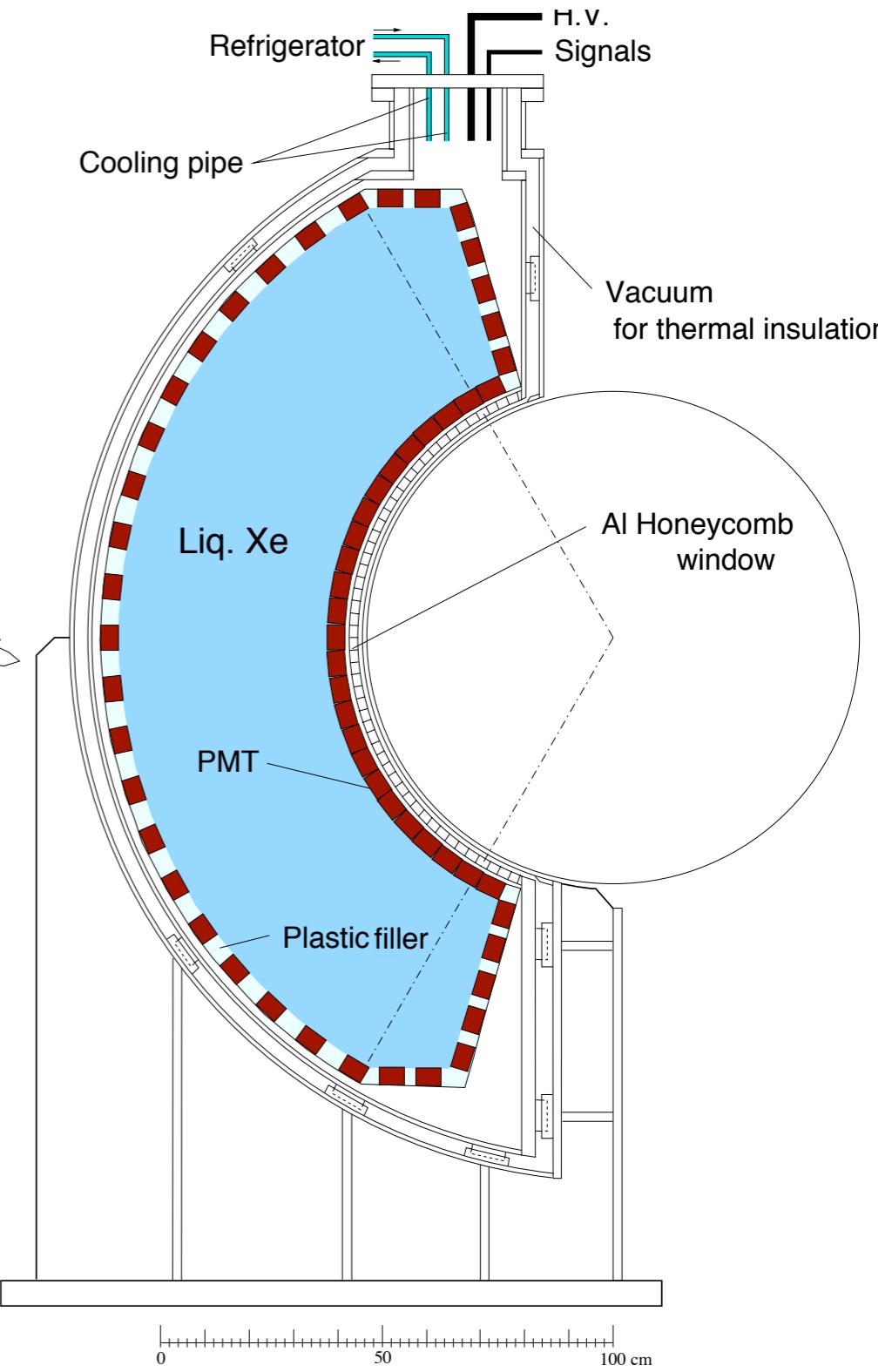
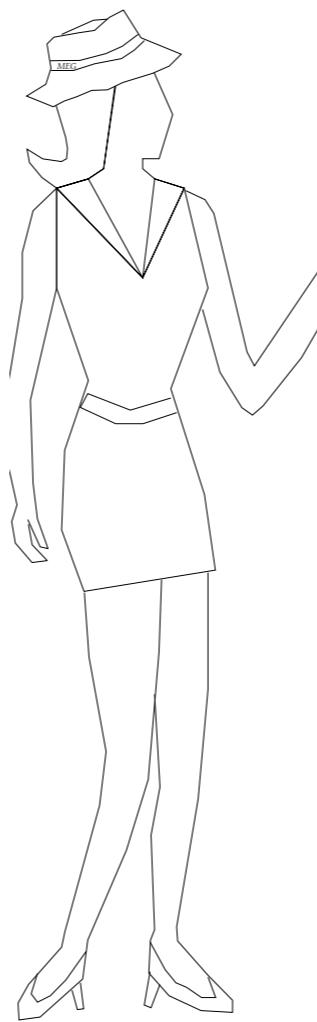


Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	$\lambda_{\text{att}}$ (cm)	$\sigma_t(\text{meas})$	$\sigma_t(\text{exp})$
G.D.Agostini	3 x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ	4.2 x 13 x 400	BC412	R1828	300	210	240
R. Stroynowski	2 x 3 x 300	SCSN38	XP2020	180	180	420
Belle	4 x 6 x 255	BC408	R6680	250	90	143
<b>MEG</b>	<b>4 x 4 x 90</b>	<b>BC404</b>	<b>R5924</b>	<b>270</b>	<b>38</b>	

Best existing TC

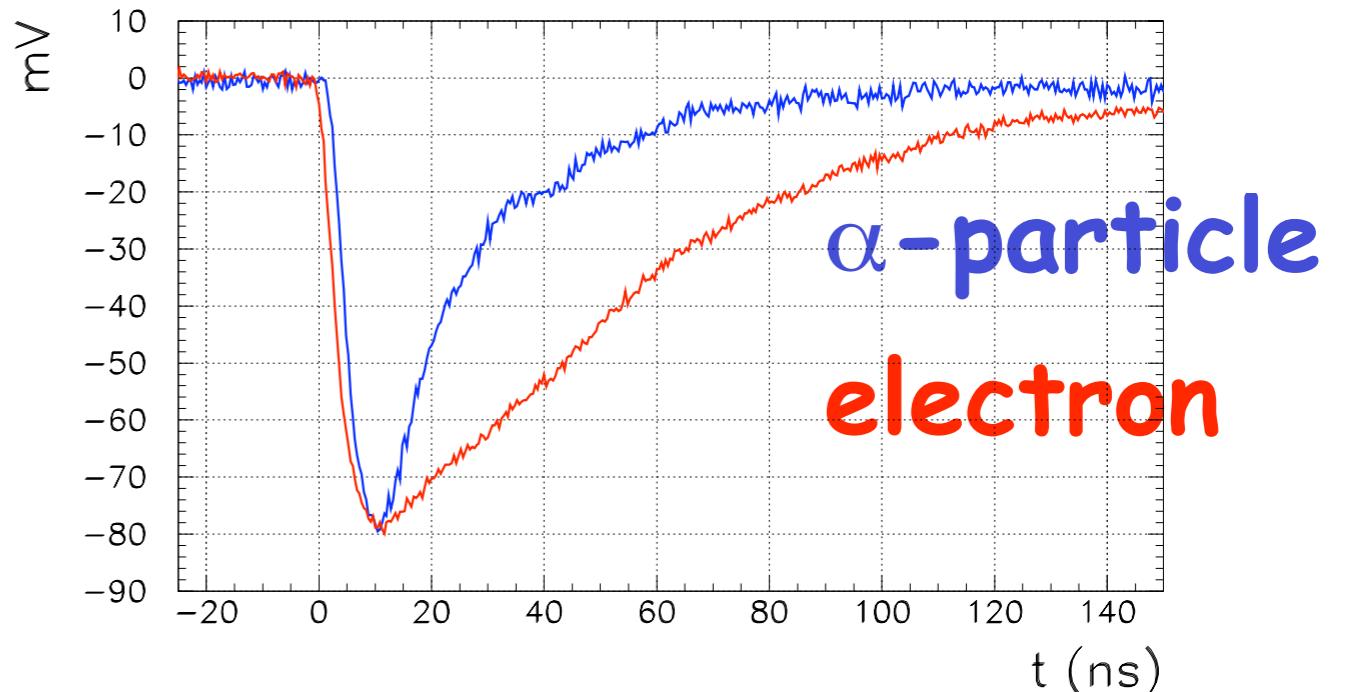
# The calorimeter

- $\gamma$  Energy, position, timing
- Homogeneous  $0.8 \text{ m}^3$  volume of liquid Xe
  - 10 % solid angle
  - $65 < r < 112 \text{ cm}$
  - $|\cos\theta| < 0.35 \quad |\phi| < 60^\circ$
- Only scintillation light
- Read by 848 PMT
  - 2" photo-multiplier tubes
  - Maximum coverage FF (6.2 cm cell)
  - Immersed in liquid Xe
  - Low temperature (165 K)
  - Quartz window (175 nm)
- Thin entrance wall
- Singularly applied HV
- Waveform digitizing @ 2 GHz
  - Pileup rejection



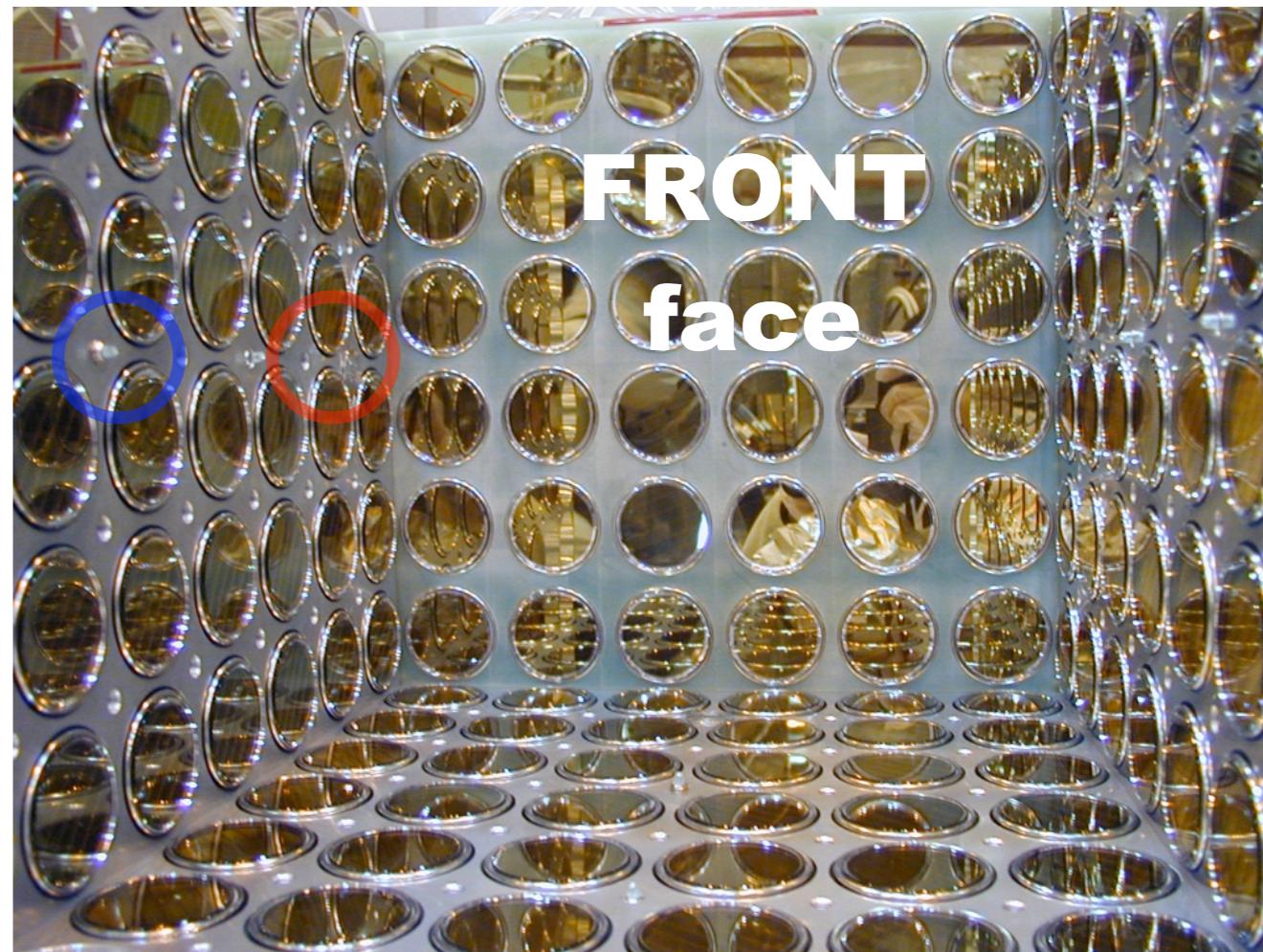
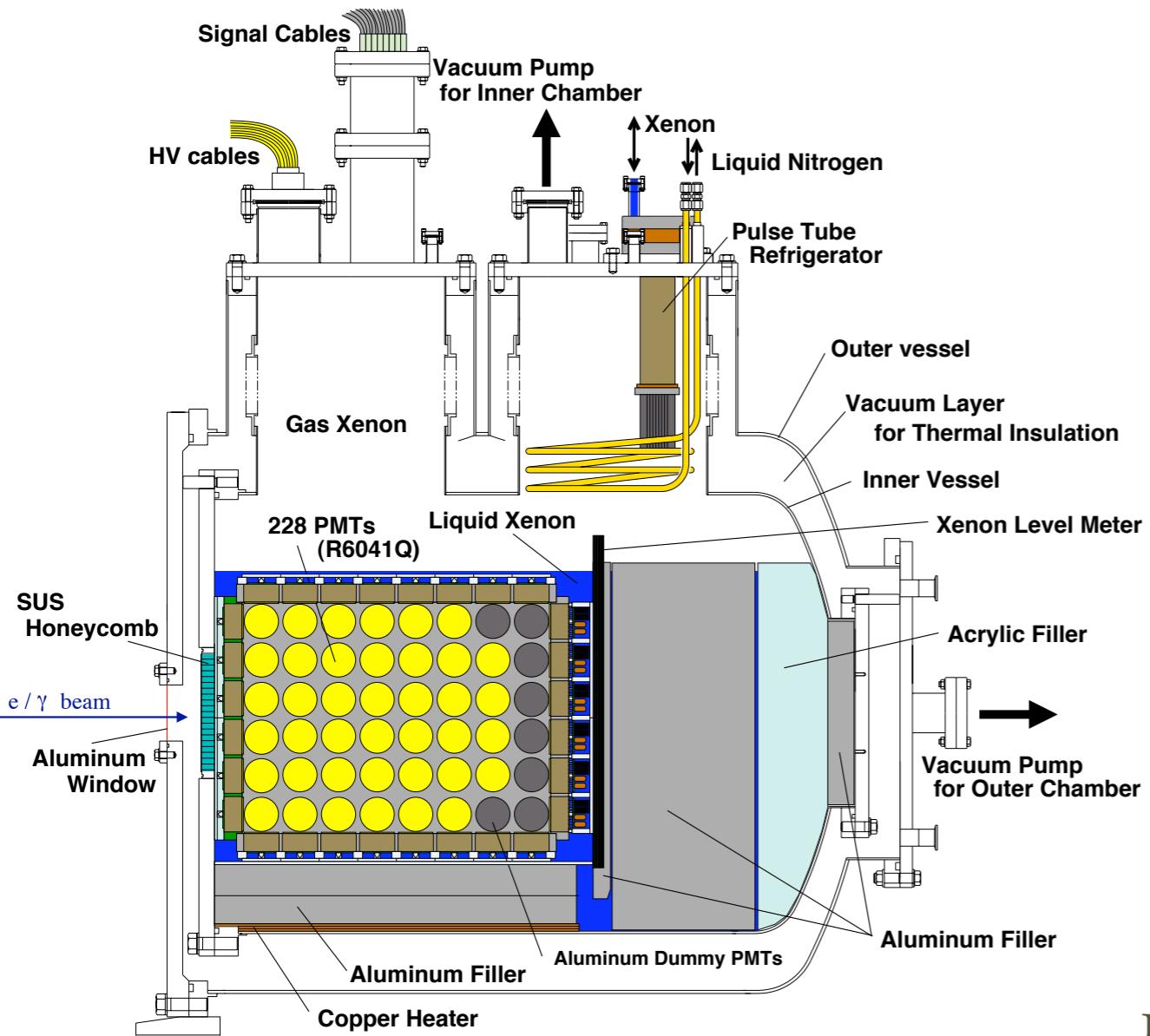
# Xe properties

- Fast
  - $\tau_{\text{singlet}} = 4.2 \text{ ns}$
  - $\tau_{\text{triplet}} = 22 \text{ ns}$
  - $\tau_{\text{recomb}} = 45 \text{ ns}$
- Particle ID
  - LY alpha =  $1.2 \times \text{LY gamma/e}$
- High LY ( $\approx \text{NaI}$ )
  - 40000 phe/MeV
- $n = 1.65$
- $Z=54, \rho=2.95 \text{ g/cm}^3 (X_O=2.7 \text{ cm}), R_M=4.1 \text{ cm}$
- No self-absorption ( $\lambda_{\text{Abs}}=\infty$ )



# The LXe calorimeter prototype

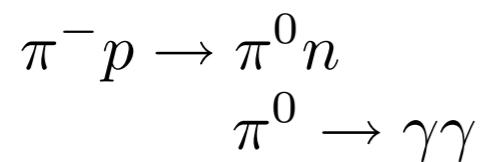
- A 100 liters, 240 PMTs **large prototype** was built and extensively tested to demonstrate the calorimeter performance
- **$\alpha$ -sources** and **LEDs** used for PMT calibrations and monitoring



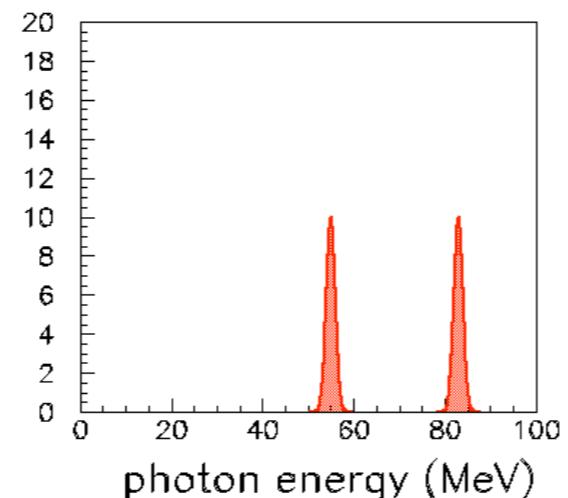


# LXe calorimeter R&D

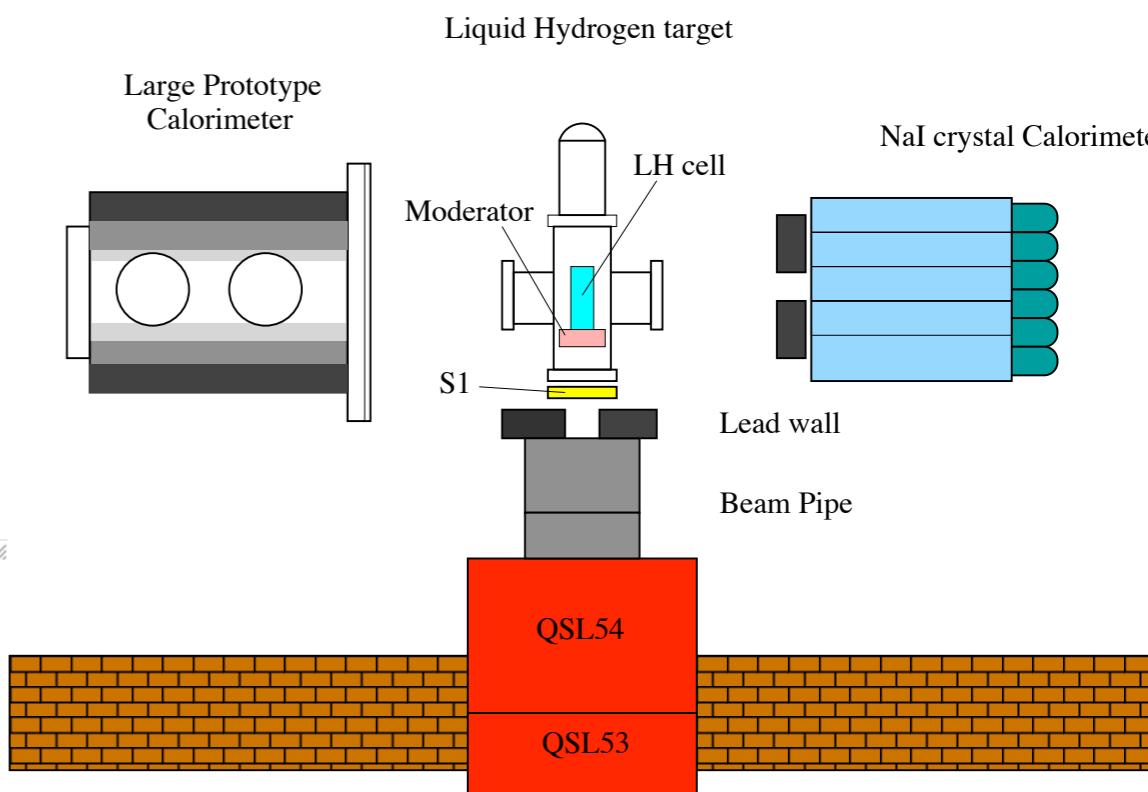
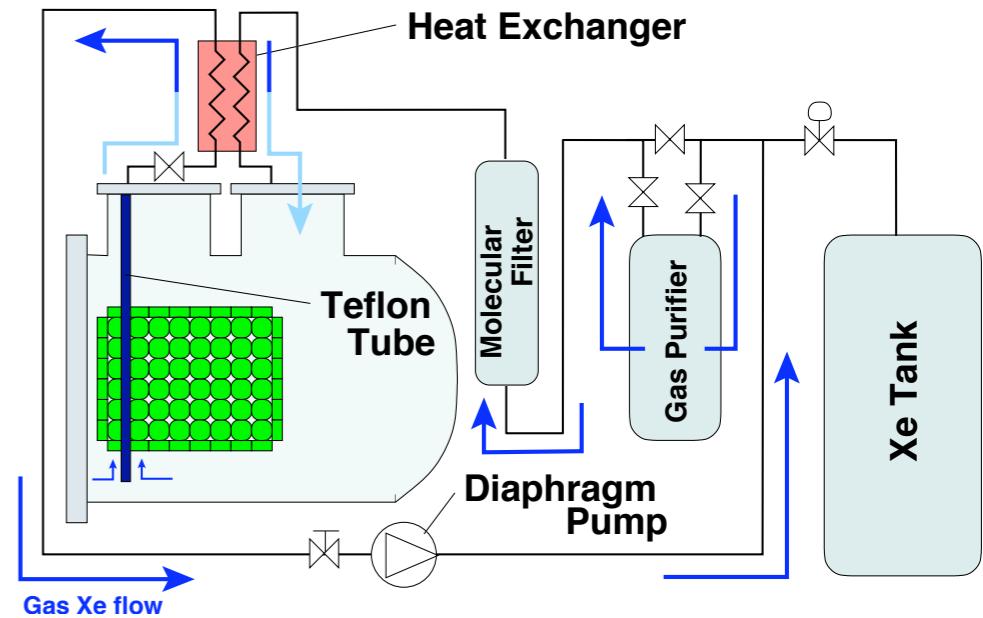
- Energy **resolution** strongly depends on **absorption**. A long R&D to insure  $L(\text{Abs}) > 3$  m with a circulation/**purification** system
- Measurement of **energy and timing resolution** with high energy photons: 55 MeV photons from pion charge exchange reaction

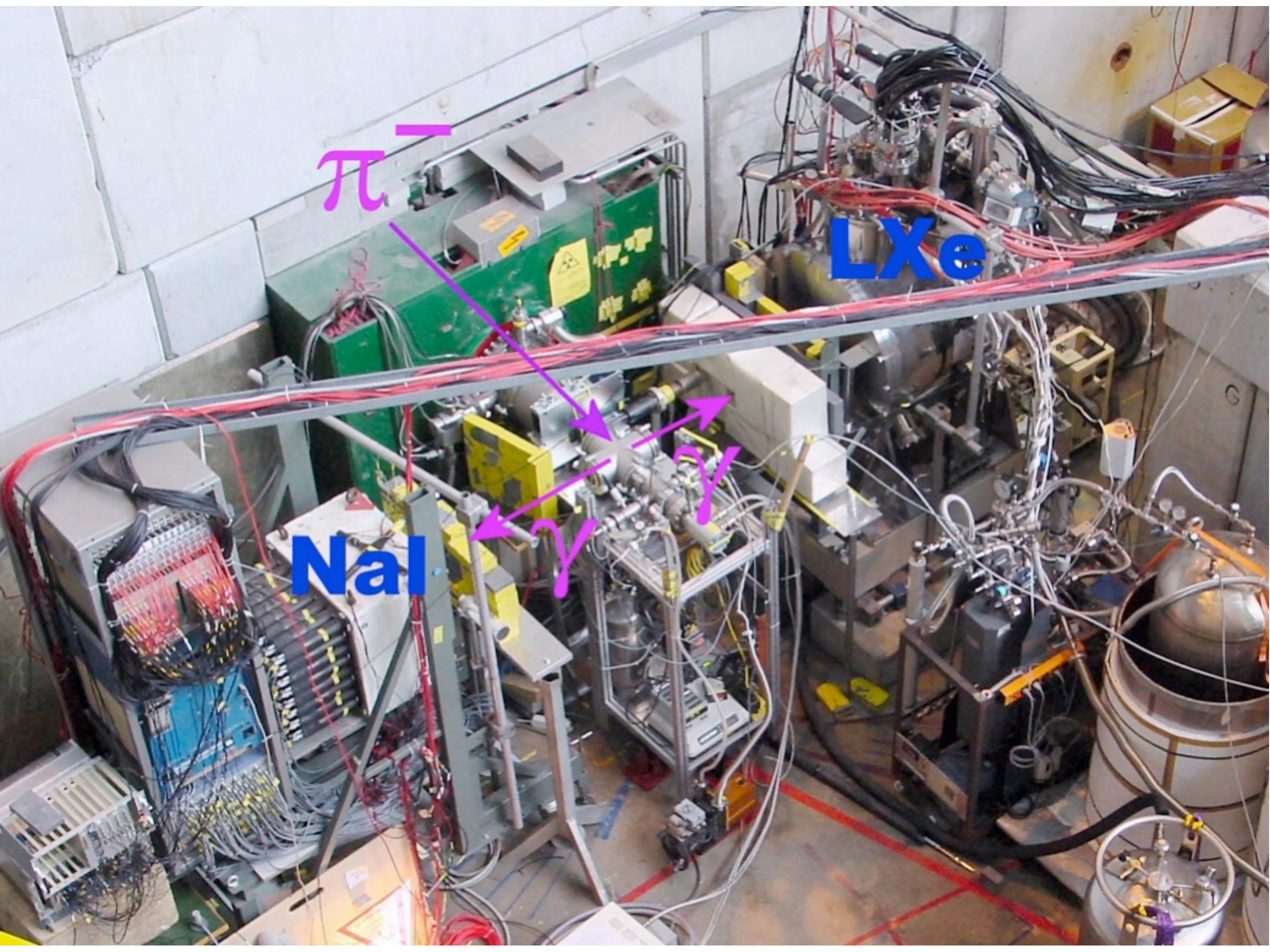


Lab Frame



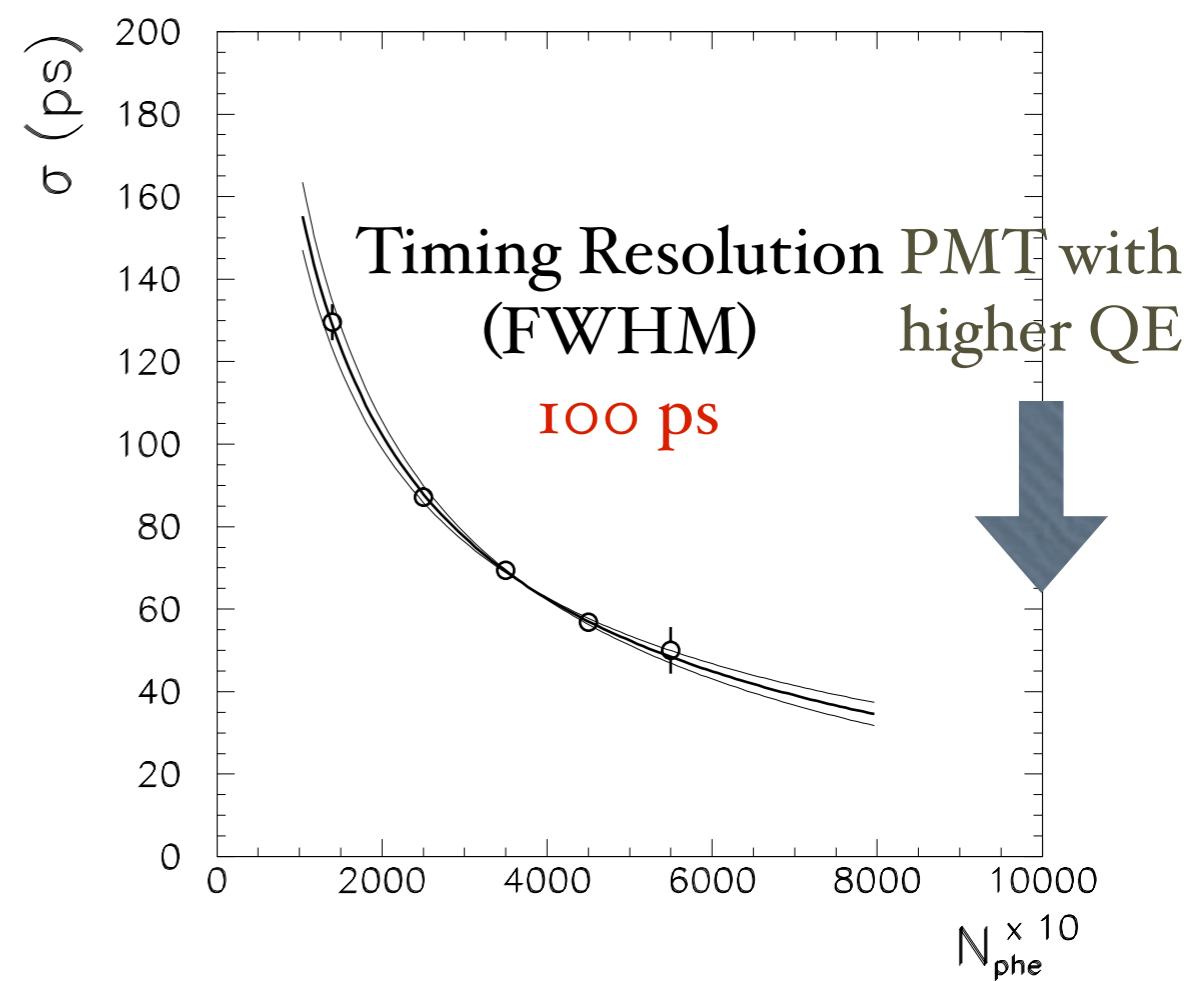
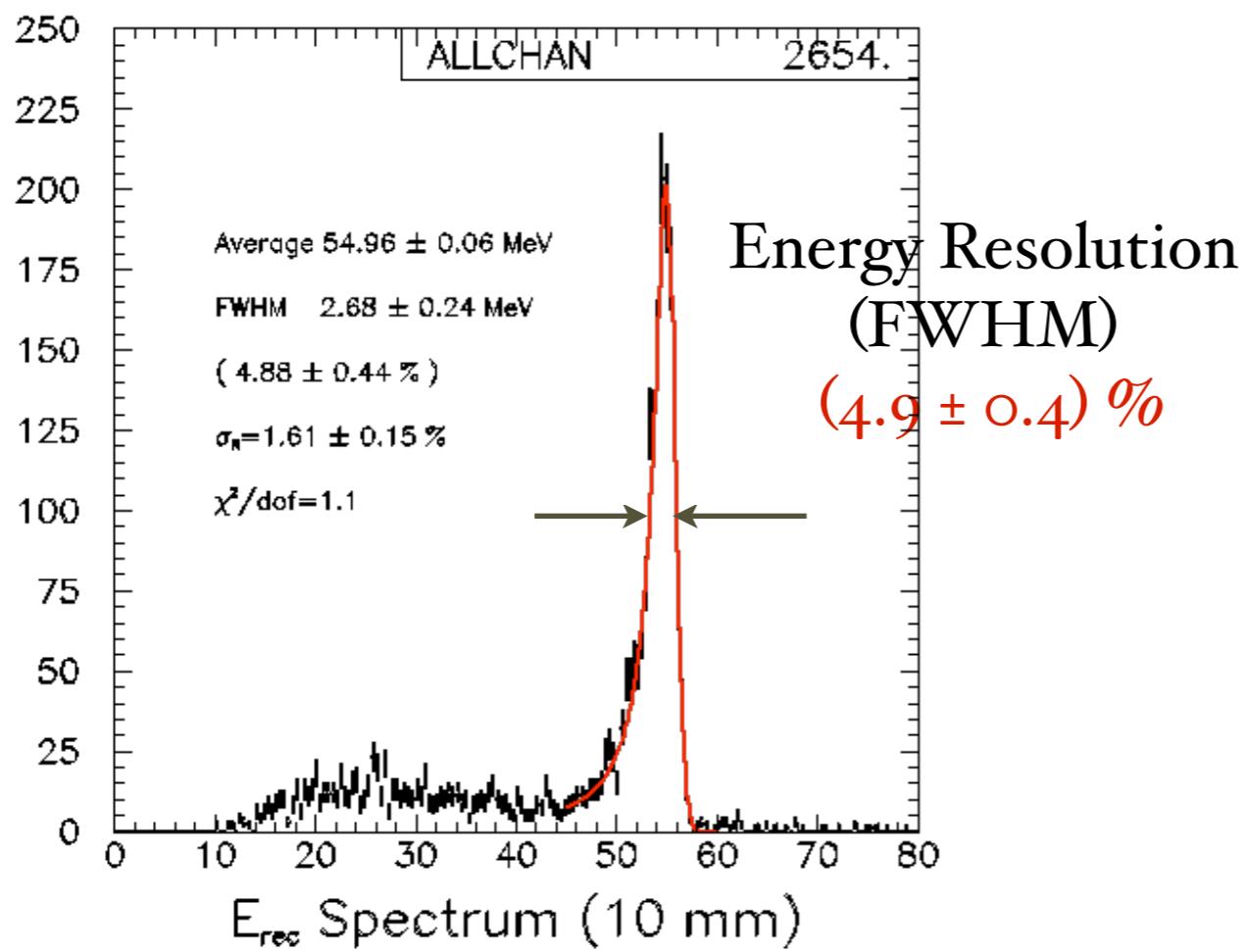
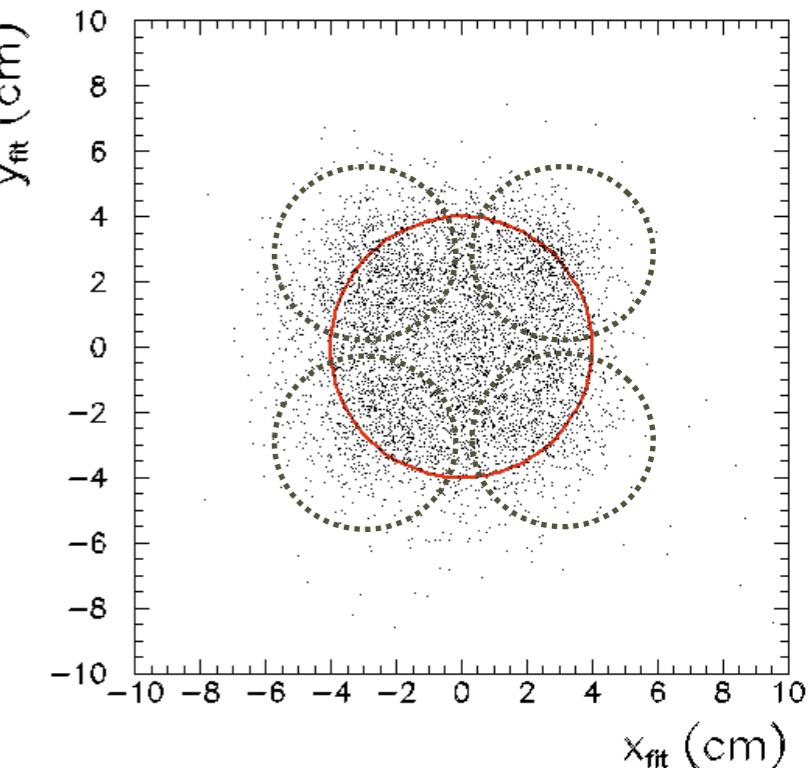
Two tests in **2003** and **2004** demonstrated the calibration procedure and the resolutions





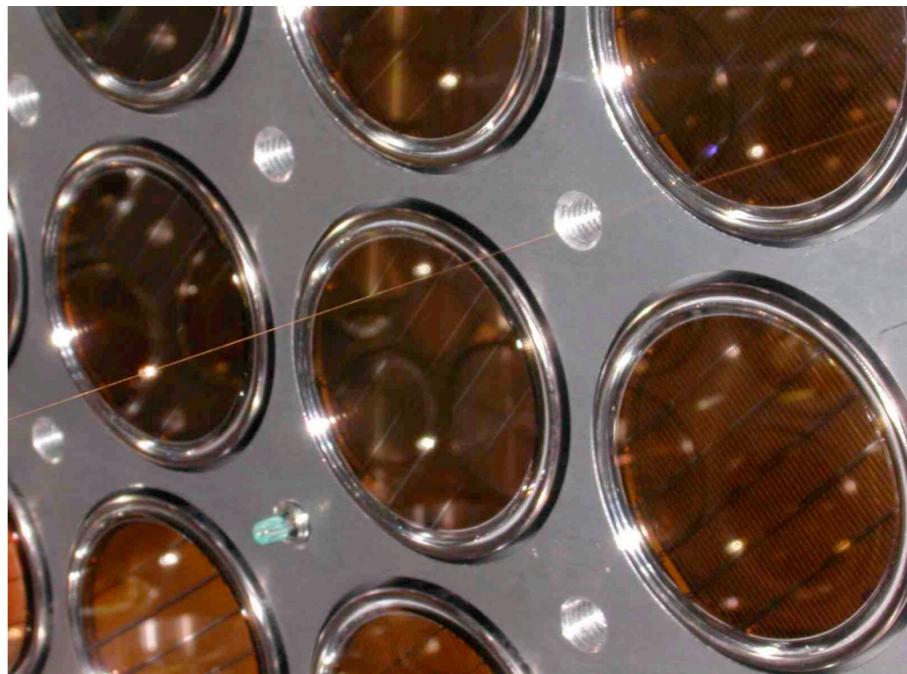
# Resolutions @ 55 MeV

- Select negative pions in the beam
- $65 \text{ MeV} < E(\text{NaI}) < 95 \text{ MeV}$
- Collimator cut ( $r < 4 \text{ cm}$ )



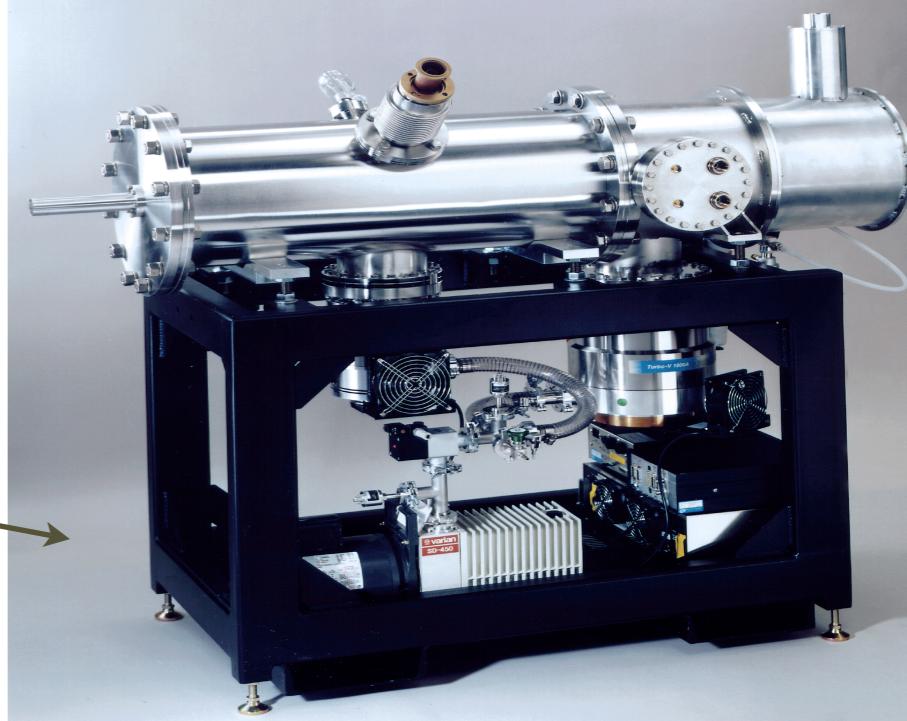
# MEG calibrations

- A reliable result depend on a constant **calibration** and **monitoring** of the apparatus
  - alpha Sources (on wires and wall)
  - Proton accelerator  ${}^7\text{Li}(p, \gamma_{17.6}){}^8\text{Be}$  design under way
  - Neutron generator  ${}^{58}\text{Ni}(n, \gamma_9){}^{59}\text{Ni}$
  - Charge exchange reaction (Panofsky)  
$$\begin{aligned} \pi^- p &\rightarrow \pi^0 n \\ \pi^0 &\rightarrow \gamma\gamma \end{aligned}$$
- Calibration frequency is different



500 keV Cockcroft-Walton

500 keV RFQ



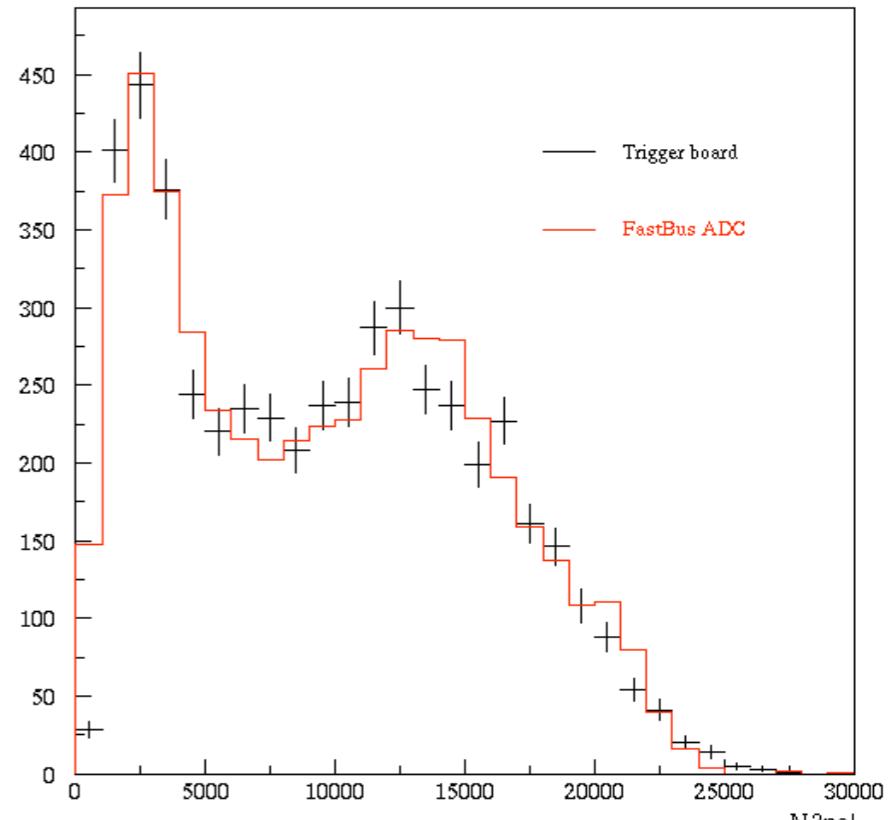
# Trigger Electronics

- 100 MHz **waveform digitizer** on VME boards that perform online pedestal subtraction
- Uses :
  - $\gamma$  energy
  - $e^+ - \gamma$  time coincidence
  - $e^+ - \gamma$  collinearity
- Built on a FADC-FPGA architecture
- More performing algorithms could be implemented



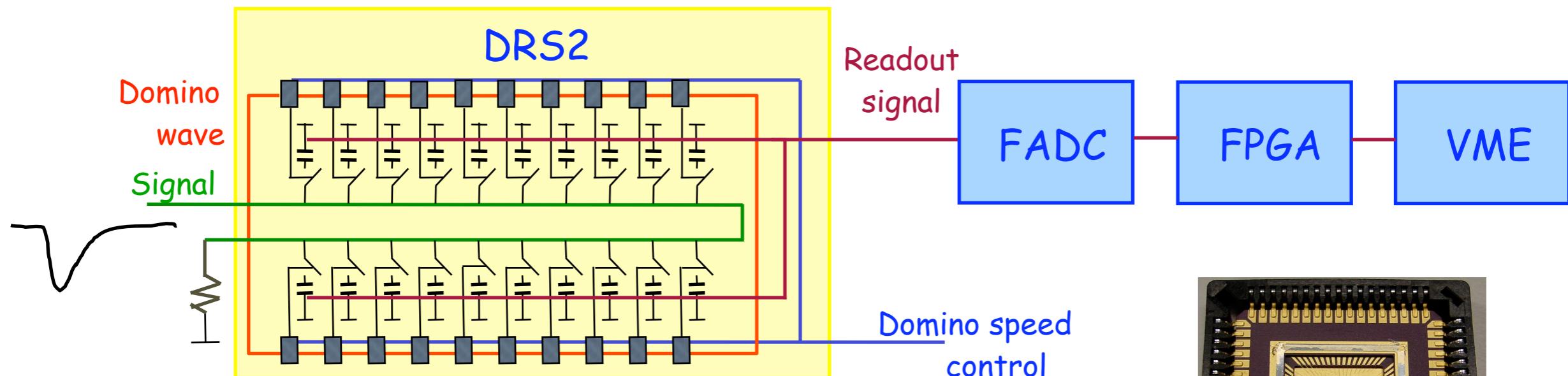
- Prototype system has been **successfully tested** on the LP
- Design of the final system is in progress
  - $\pi^0$  data
  - Charge spectrum
  - Only 32 PMT

❖ Beam rate  $10^8 s^{-1}$   
❖ Fast LXe energy sum  $> 45\text{MeV}$   
 $2 \times 10^3 s^{-1}$   
gamma interaction point (PMT of max charge)  
 $e^+$  hit point in timing counter  
❖ time correlation  $\gamma - e^+$   $200 s^{-1}$   
❖ angular correlation  $\gamma - e^+$  **20 s<sup>-1</sup>**



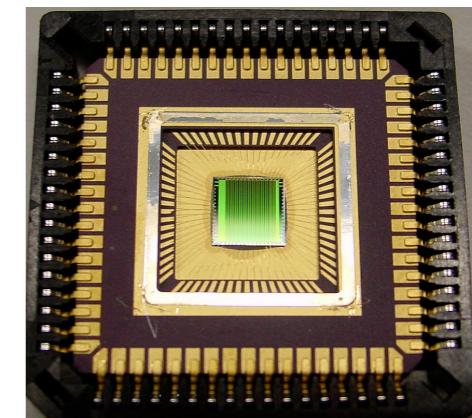
# Readout electronics

2.5 GHz Waveform digitization for all channels

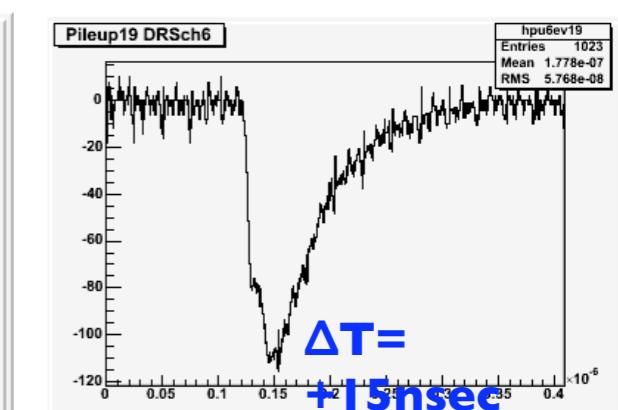
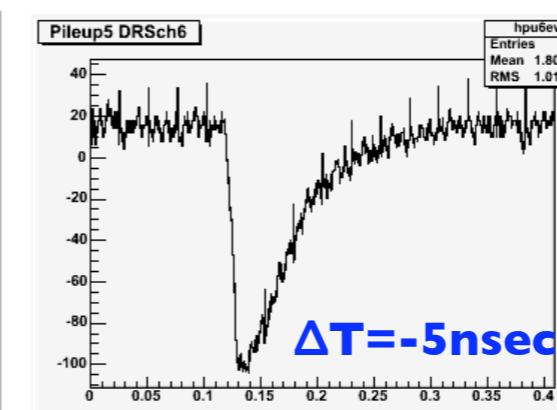
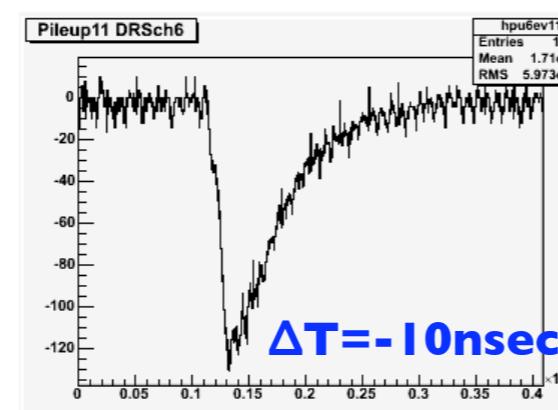
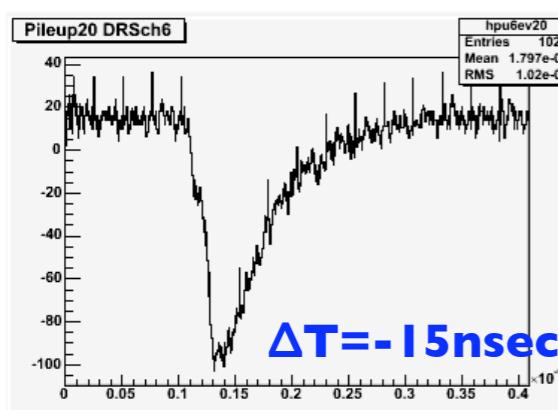


DRS2 chip (Domino Ring Sampler)

- Custom sampling chip designed at PSI
- 2.5 GHz sampling speed @ 40 ps timing resolution
- Sampling depth 1024 bins for 8 channels/chip
- Data taken in charge exchange test to study pile-up rejection algorithms



Original



# MEG sensitivity

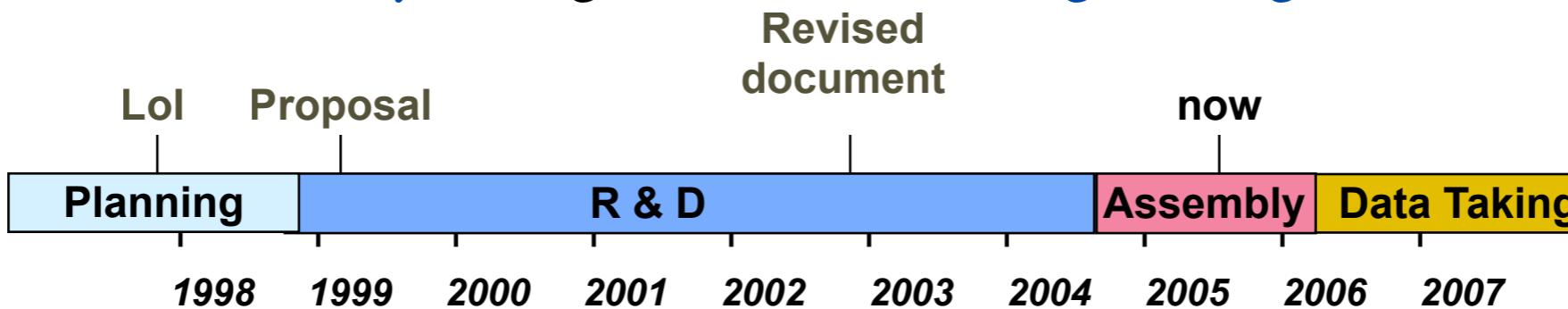
- Computation of the **sensitivity** based on the measured **resolutions**

FWHM $E_\gamma/E_\gamma$	5 %
FWHM $E_e/E_e$	0.9 %
$\delta t_{e\gamma}$	105 ps
$\delta\theta_{e\gamma}$	23 mrad

- The resolutions determine the **accidental background**
- For a given background we choose **R( $\mu$ )** and **running time**.
  - $\text{BG} = 0.5$  events
  - $\text{R}(\mu) = 1.2 \times 10^7 \mu/\text{sec}$
  - $T = 3.5 \times 10^7 \text{ sec}$  (2 years running time)
  - $\Rightarrow \text{SES} = 6 \times 10^{-14}$  ( $1.7 \times 10^{13}$  muons observed)
- NO candidate  $\Rightarrow \text{BR}(\mu \rightarrow e\gamma) < 1.2 \times 10^{-13}$  @ 90% CL
- Unlikely fluctuation (4 events)  $\Rightarrow \text{BR}(\mu \rightarrow e\gamma) \approx 2.4 \times 10^{-13}$

# Summary and Time Scale

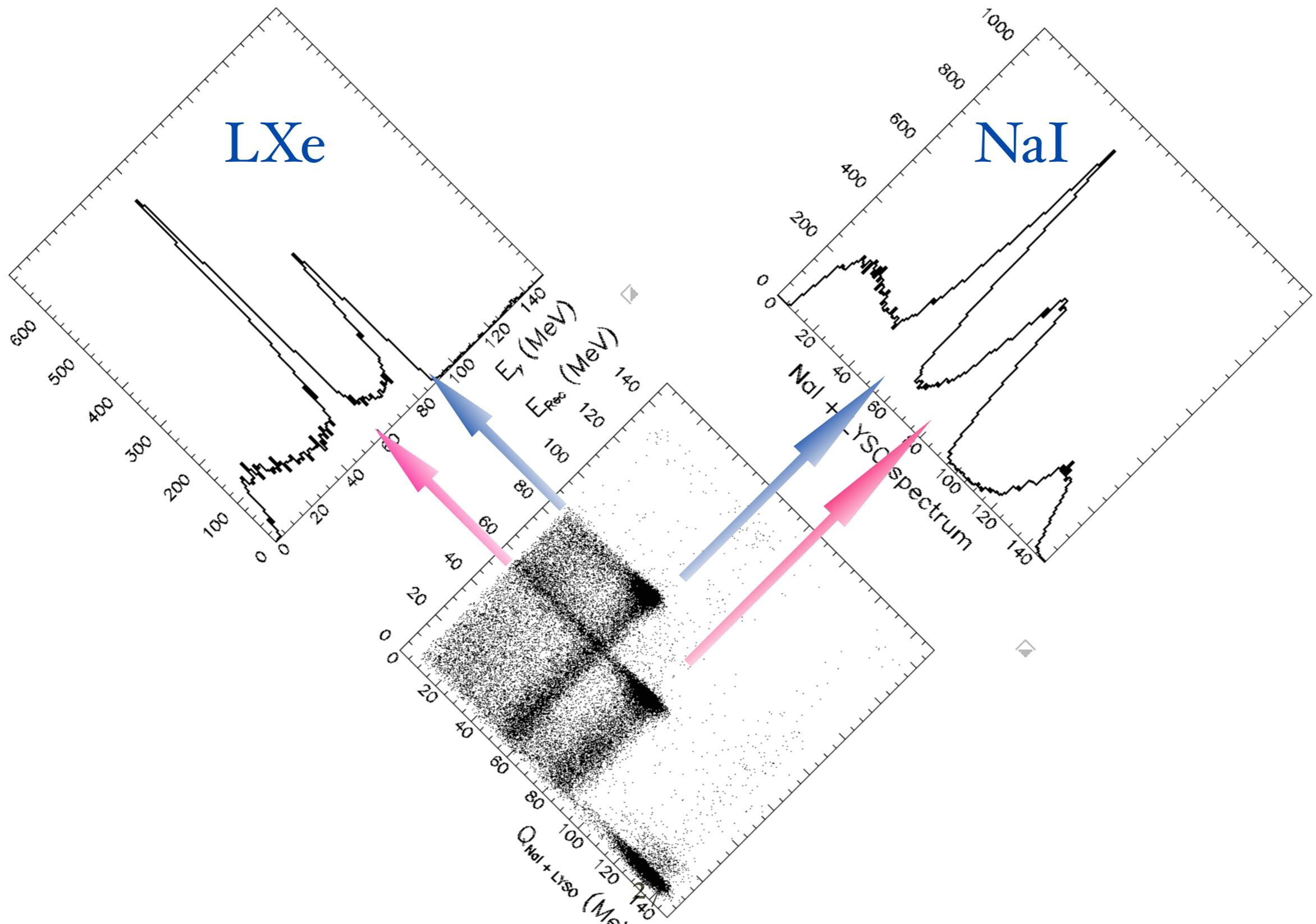
- The experiment may provide a clean indication of **New Physics** or a strong constrain on SM extensions
- Measurements and detector simulation make us confident that we can reach the **SES of  $6 \times 10^{-14}$**  to  $\mu \rightarrow e\gamma$  ( $BR = 1.2 \cdot 10^{-13}$ )
- Final prototypes of (almost) all subdetectors were measured
  - Liquid Xe calorimeter Large Prototype
  - Timing counters
- Detector **assembly** during end 2005/2006 **engineering run 2006**



More details at

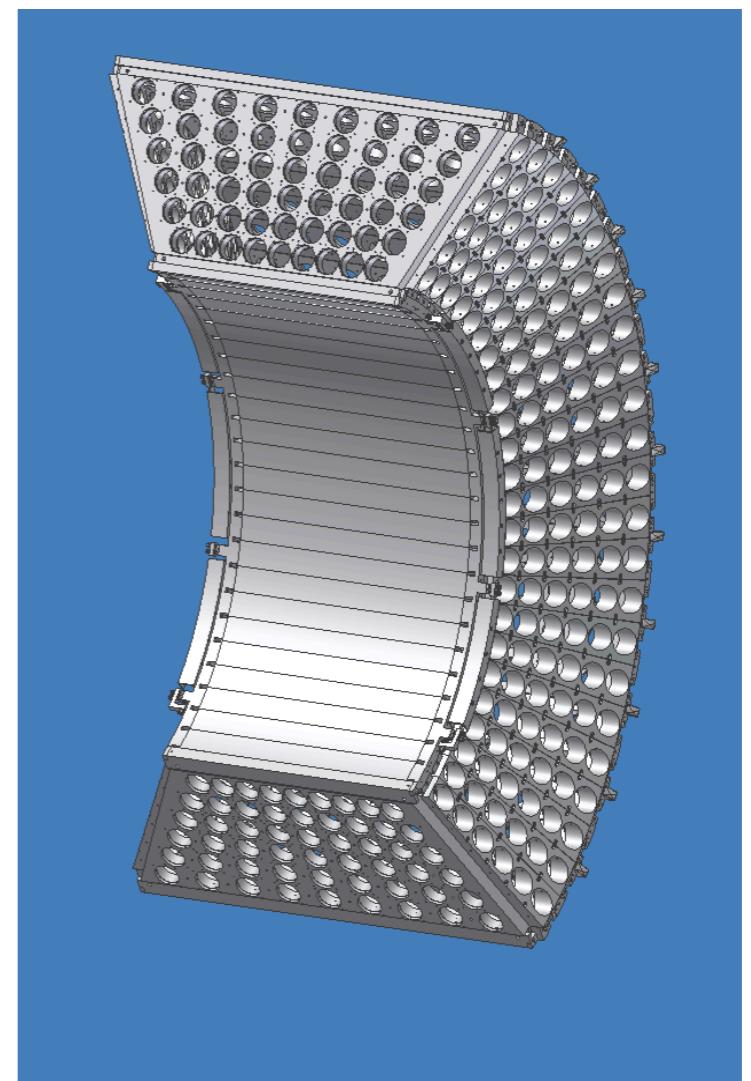
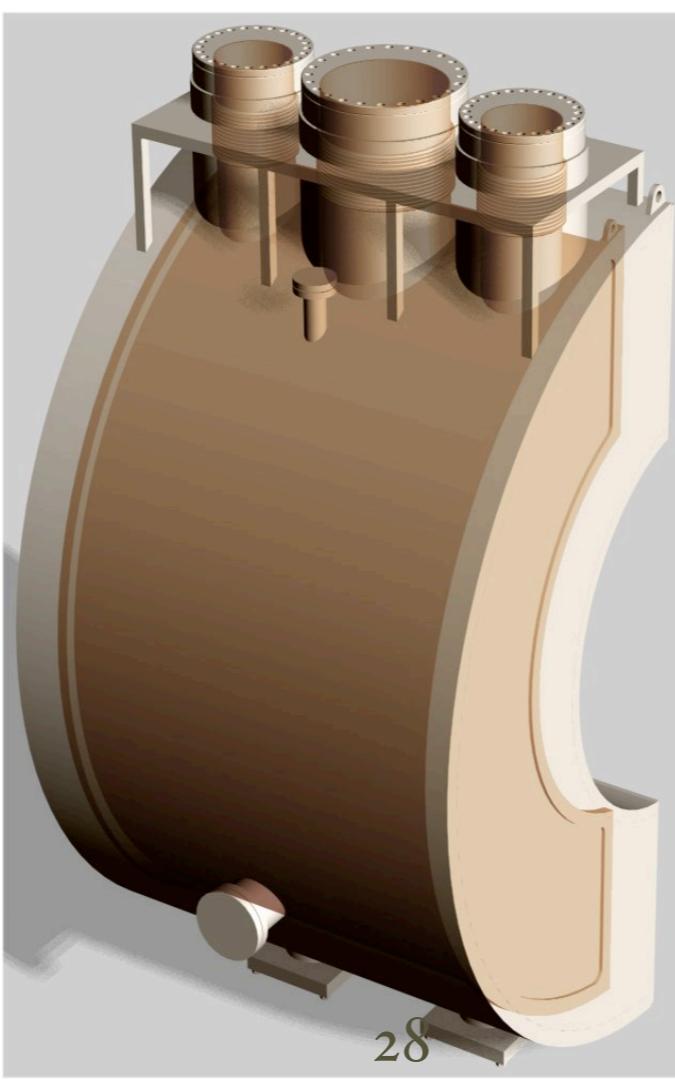
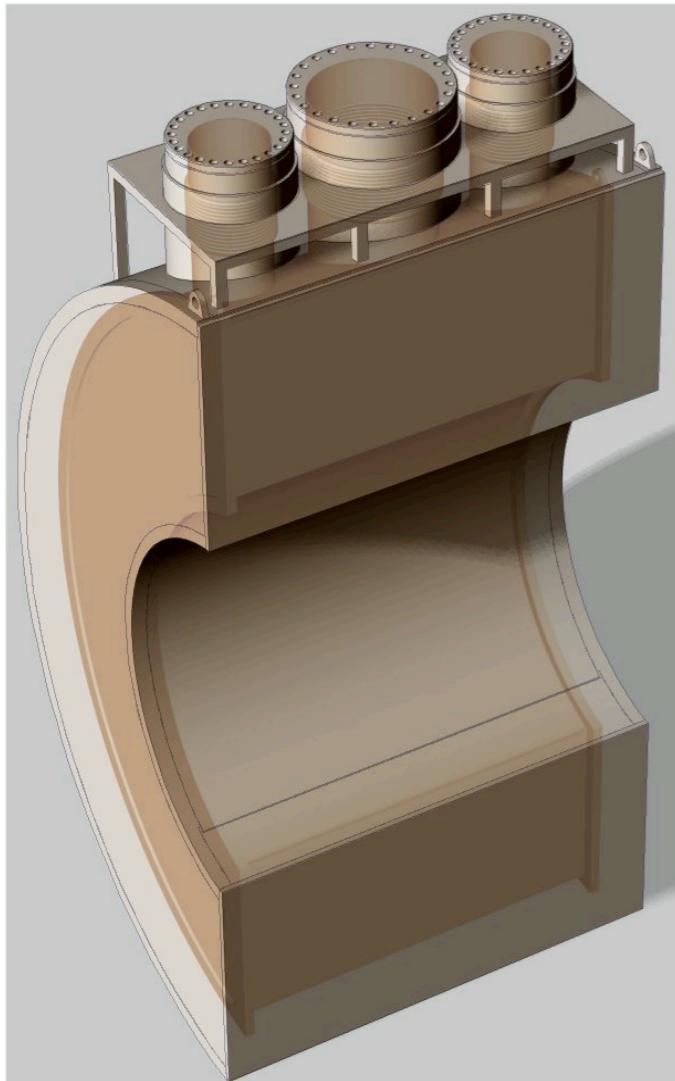
<http://meg.psi.ch>  
<http://meg.pi.infn.it>  
<http://meg.icepp.s.u-tokyo.ac.jp>

- In the **back-to-back** raw spectrum we see the **correlation**
  - $83 \text{ MeV} \Leftrightarrow 55 \text{ MeV}$
  - The  $129 \text{ MeV}$  line is visible in the NaI because Xe is sensitive to neutrons ( $9 \text{ MeV}$ )



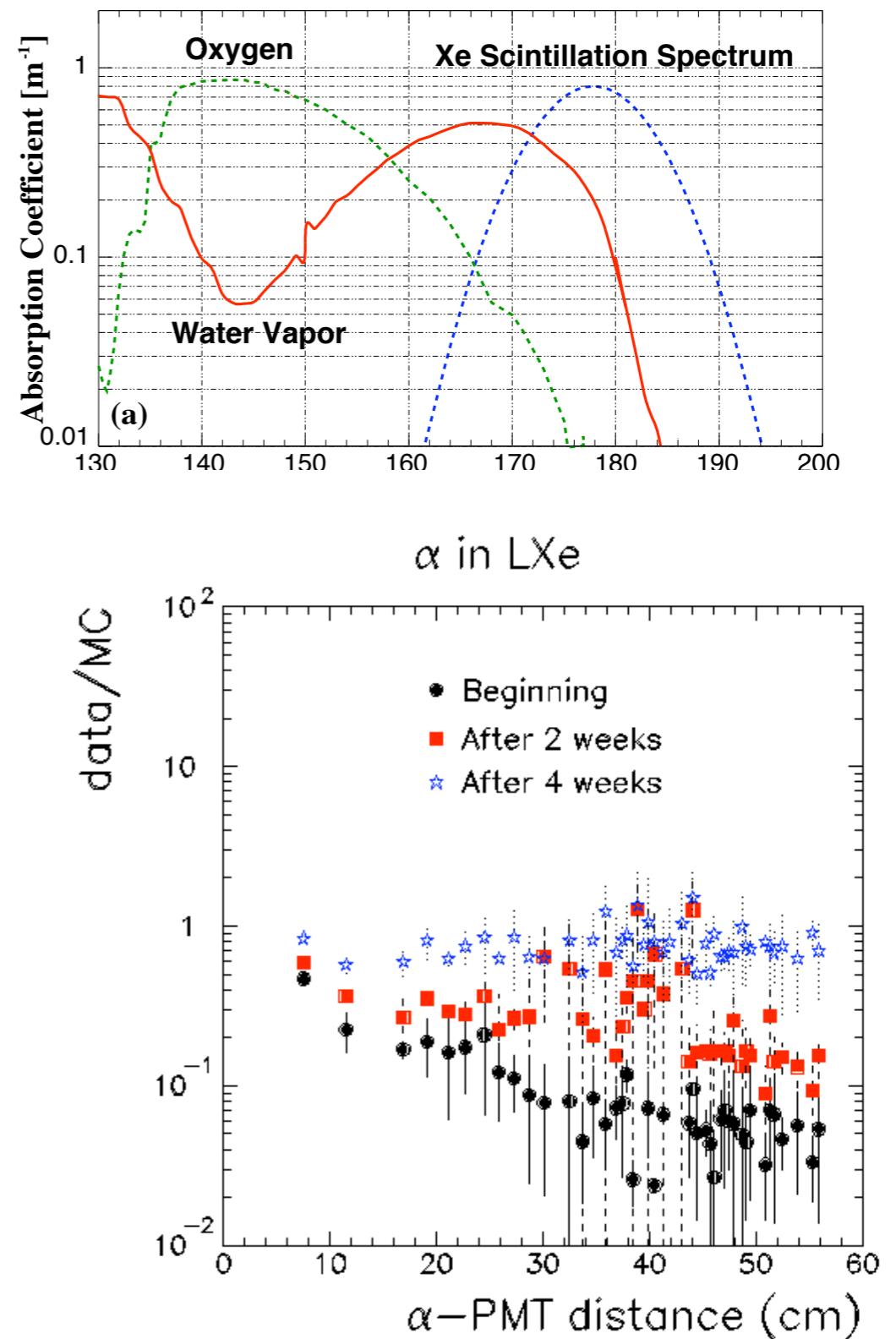
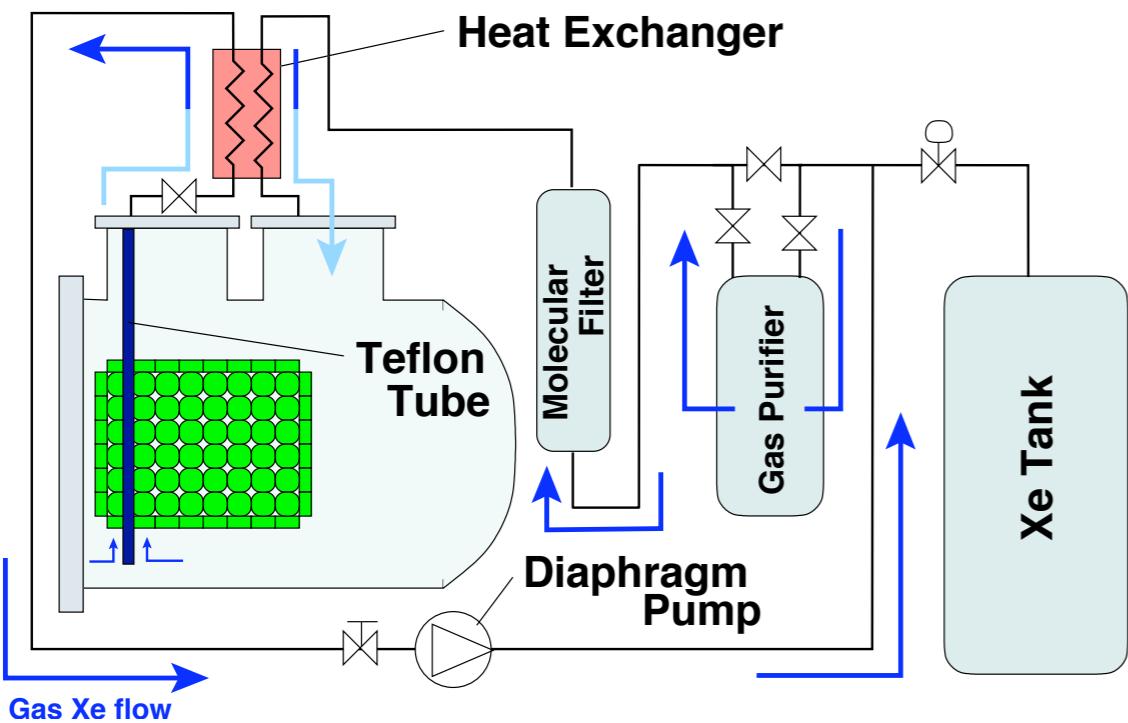
# Calorimeter construction

- Built by SIMIC (Italy) on a japanese-italian project
- Low magnetic permeability stainless steel
- Delivery January 2006 @ PSI
- Test of all the >800 PMTs in Pisa and at PSI



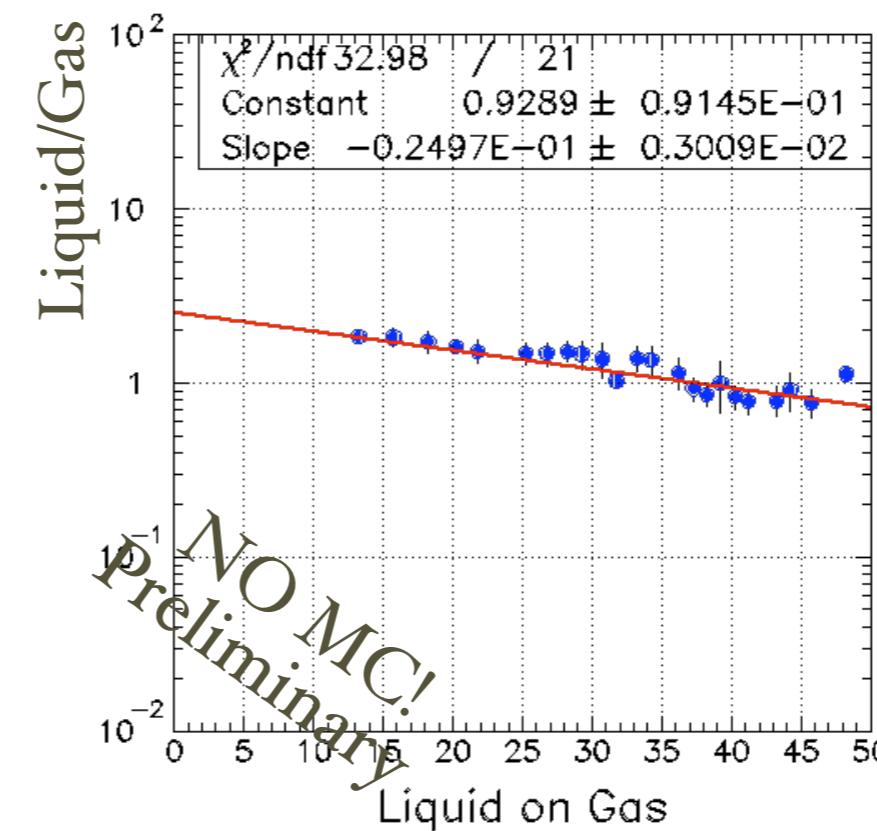
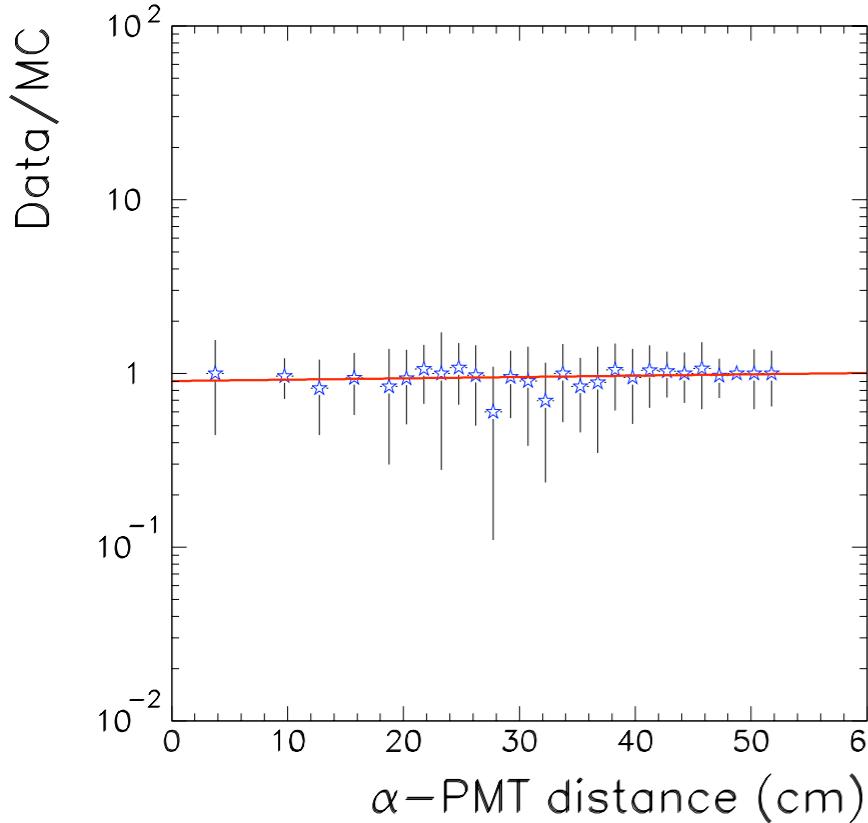
# Measurement of absorption

- Energy **resolution** strongly depends on **absorption**
- We developed a method to **measure the absorption length** with **alpha sources**
- We added a **purification system** (molecular sieve + gas getter) to reduce impurities below ppb



# $\lambda_{\text{Abs}}$ measurement

- It is possible to estimate a lower **limit** on the xenon **absorption length**
- Typical plots shown
  - $\lambda_{\text{Abs}} > 125 \text{ cm}$  (68% CL) or  $\lambda_{\text{Abs}} > 95 \text{ cm}$  (95 % CL)
  - LY  $\sim 37500$  scintillation photons/MeV (0.9 NaI)



Attenuation = Rayleigh  
 $\lambda_{\text{Att}} \sim 40 \text{ cm}$   
 L.Y.(liquid)  $\sim 3 \times$  L.Y.(gas)